Analysis of Power Balancing with Fuel Cells & Hydrogenproduction Plants in Denmark

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ANALYSIS OF POWER BALANCING WITH FUEL CELLS & HYDROGEN PRODUCTION PLANTS IN DENMARK

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PROJECT REPORT
MARCH 2009

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EXECUTIVE SUMMARY

In the past few years electric vehicles and other electric storage devices ability to hybridize the electric grid have gained increasing interest. Electric vehicles and their ability to hybridize the electric grid are especially interesting in a Danish context for two reasons. There is limited storage capacity in the Danish electric grid and it is therefore expensive to hybridize (balance power and energy supply and usage) in the Danish electric grid. An increasing use of fluctuating renewable energy, especially in the form of electricity from wind power, will make it more and more difficult and expensive to hybridise the Danish electricity grid. On top of this electric vehicles are getting closer and closer to the market because of better electric drive trains, better batteries, better fuel cells etc. Furthermore it has become evident that CO2 reduction targets cannot be met by internal combustion driven vehicles. Finally most likely there will be a drop in worldwide oil supply within a timeframe of 5 – 20 years.

Analyses within the possibility to use electric vehicles to hybridise the electric grid have primarily been conducted on battery electric vehicles. There are however other ways to supply electric vehicles with electricity than to use batteries. One such candidate is to use electricity from hydrogen powered fuel cells.

Since hydrogen production and the use of it in fuel cells have other capabilities and characteristics than the use of electricity from batteries on a number of points, one have to conduct new analysis’s when it comes to the hybridization of the electric grid.

Given the CO2 reduction challenges the world face it is assumed that a prerequisite for vehicles of the future is that they are low CO2 emitters.

The purpose of this report is therefore to analyse how future hydrogen production and hydrogen use in stationary fuel cells as well as fuel cells in vehicles can help balance power and energy in a future electric grid with high shares of fluctuating renewable energy.

Emphasis is on future hydrogen production using high temperature solid oxide electrolysers and the use of this it in 500.000 hydrogen fuel cell vehicles (HFCV) or in 500.000 plug-in hybrid hydrogen fuel cell vehicles (hybrid HFCV). These findings are compared to the findings for 500.000 ICE and battery electric vehicles (BEVs). The HFCV is a pure hydrogen vehicle with energy storage in the vehicle in hydrogen tank(s). This kind of car does however also have an electric energy storage that is used for acceleration and regenerating braking. The hybrid HFCV on the other hand is a hybrid between a battery electric vehicle and a HFCV, since it has a battery that can be charged from the electric grid, as well as (a) hydrogen(s) tank that can be refuelled at a hydrogen station. The hybrid HFCV in this case has a battery electric range of 60 km. On longer trips and/or at high speeds or/and when using the heater or aircon. the fuel cell will kick in and supply energy for a total range of 600 km. There is a very high degree of uncertainty regarding the number of vehicles in which years, since we have not entered the S-curve yet.

Results of the analyses of renewable energy systems and socio-economy conducted by Aalborg University
Analysis made by Aalborg University in the project show that vehicles using hydrogen are generally better at using excess electricity, i.e. to integrate fluctuating renewable energy than the battery electric vehicles. Already in 2012 the battery electric vehicles, which have the ability to charge at the right times, as well as hydrogen based vehicles may remove the excess electricity consumption. Although the hydrogen production at electrolysers may be able to remove excess electricity production, the efficiency is rather low. The battery electric vehicles have the lowest fuel

consumption, already in the present energy system. The CO2-emissions are also the lowest for the battery electric vehicles in the current and future energy systems.

For both the battery electric vehicles as well as the plug-in hybrid battery-hydrogen fuel cell vehicles it is important that the electricity demand is flexible. In the dump charge situation the potential to reduce the fuel consumption, CO2-emissions and to integrate fluctuating renewable energy is improved with the ability to charge at times with wind power. This becomes increasingly important with more wind power, and can already be identified in 2012.

The energy system analyses conducted here represents systems with plenty of excess wind power. The results presented above are also true for the 2030 energy system with 50 per cent wind power and 100 per cent renewable energy system for 2050. In the future however, it is likely that both electrolysers and battery electric vehicles will have to compete with other technologies. In this situation the solutions with the lowest electricity demand is best of.

The socio-economic results reveal that the battery electric vehicles have lower costs than all the configurations of hydrogen fuel cells vehicles, also in hybrid solutions. This is the case in all the energy systems analysed towards 100 per cent renewable energy systems as well as for low, medium and high fuel prices. Thus the battery electric vehicles are less vulnerable to fluctuating energy prices. This is also the case when including electricity use for the heating systems in the battery electric vehicles.

With long term fuel costs between 87 and 129 $/bbl, as recommended by the IEA and the Danish Energy Authority, the socio-economic costs of battery electric vehicles are lower than for conventional ICE powered vehicles. Please note that no externalities have been included in the socio-economic costs other than indirectly by the CO_2-trading scheme. If such costs had been included the highest costs would be connected to the transport scenarios with the highest use of fuels, especially fossil fuels. Such costs does not change that the battery electric vehicles have lower socio-economic costs than HFCV. In the 100 per cent renewable energy system the lowest fuel demand is for the battery electric vehicles. Although this energy system has extreme amounts of excess electricity production the hydrogen solutions cannot compete with the battery electric vehicles.

The battery electric vehicles represent the most promising solution for integrating renewable energy based on the analyses presented here. These vehicles also represent an efficient strategy for local consumption of renewable energy, which can reduce the strain on the overall system stability and the demand for transmission of electricity.

The biofuels analysed represents low cost solutions comparable to conventional technologies, however the fuel consumption in these transport scenarios are rather high, and such biomass can be used to replace fuel in the electricity and heat production for e.g. hydrogen or battery electric vehicles.

The analyses presented here are based on the fact that the vehicles have the same size, however the range of battery electric vehicles is 200 km, which can cover 98 per cent of the total Danish transport demand, considering the driving ranges. Even with a range of 100 km, such vehicles can cover 85 per cent of the transport demand. The results regarding fuel consumption, socio-economy, integration of fluctuating renewable energy sources and the CO_2-emissions are rather robust, which has been documented through sensitivity analyses, of e.g. higher energy consumption pr. km. For the socio-economic results the following issues areas should be noted:

The results of the hydrogen vehicles are primarily dependent on:

- the flexibility of electrolysers for producing hydrogen at times with wind power
- very low costs and highly efficient hydrogen storage and distribution

the development of efficient fuel cell systems for vehicles

The results of the battery vehicles are primarily dependent on:
Lower costs of batteries
Longer life expectance of batteries

In the first phases of the implementation of battery electric vehicles, a solution may be to introduce smaller vehicle with shorter ranges, until the batteries are improved. The flexibility of electrolysers are uncertain and represents a problem for integrating fluctuation renewable energy, also in future high temperature electrolysers. The fuel consumptions and CO_2-emissions are larger than for current vehicles until we have more than 50 per cent wind power in the hydrogen vehicle transport scenarios. Also, if hydrogen is not produced according to the wind power production at this time, the fuel consumption and CO_2-emissions may remain larger than for the current vehicles.

Results of the business case and market economic analyses conducted by H2Logic
According to H2 Logic and results and development trends from the major car manufacturers the differences in range between the BEV and HFCV vehicles significantly influences the analysis results from by Aalborg University. The difference range gives the BEV vehicle a price advantage on the cost of the onboard storage compared to the HFCV. Results from General Motors suggest that cost of a HFCV system could be $3.000 at 500 km range, whereas the cost for a battery system at 500 km range could be as high as $50.000. Further vehicle user patterns and behaviour are more complex than the statistic km per day allocation shows. Trips at high speed outside cities reduce the range of the BEV as well as the power consumption for cabin heating, thus not all end-users and vehicle types may realistically be able to use batteries alone. Further for BEV to provide a similar access to refuelling of energy as gasoline and hydrogen cars will require access to recharging facilities at a large share of all public parking places in Denmark, requiring a significant investment. Even with these facilities in place recharging will require change in user behaviour and will not be as fast as refuelling of gasoline and hydrogen. These issues are the opinion of H2 Logic.

Other results
A working prototype of a stationary fuel cell system that is able to deliver power to the grid, based on a demand-signal from the utility company was developed in the project. The (re)wirering of internal relays and the programming of the PLC in a stationary fuel cell system are described.

Batteries can be used both up- and down for primary reserves, for regulating and as spinning reserves. Small changes in depth of discharge (DOD) do not tear as much as deep DoD. Therefore batteries can take many shallow cycles (defined as less than 3 % change in DoD) without them being worn significantly. Batteries are therefore well suited for providing primary reserves. In general the deeper the DoD, the less suitable is batteries for providing hybridization of the electric grid.

Electrolysers that are e.g. running at 70 % load can be used as both energy suppliers and energy users in the electric grid. If there is a surplus of energy in the electric grid the electrolyser can increase the load (to e.g. 90 %) and if there is a deficit of energy in the electric grid the electrolyser can be running at a lower load factor (at e.g. 50 %). The cells of a Solid Oxide Electrolyser (SOEC) have fast regulation abilities (from 0% to 100% power in less than a few seconds) if the cell temperature is kept at the maximum operating temperature. SOEC can therefore be used for up and down regulating as well as spinning reserves if constructed for this purpose and if the cells are developed. It does however have to be noted that the startup time for a cold SOEC is several hours of which reason the SOEC have to be kept warm at all times if it is to be used to hybridize the electric grid.

Start and stops greatly reduce the lifetime of fuel cells. In general the longer and the more steady the energy production from the fuel cells, the longer a lifetime (measured in hrs) one can expect.

Fuel cells can be used as primary reserves, for regulating and as spinning reserves (up only – that is energy from fuel cells to grid), but due to the wear of start and stops fuel cells will most likely only be used for spinning reserves and for peak power a few times a year. For sustained periods of high prices (over several hrs) other means to produce electricity will most likely be more fuel-, cost- and CO2- efficient.

From a private economic perspective the owner of a BEVs or a hybrid HFCVs one can expect to receive a considerable amount of money if one puts ones vehicles at the disposal of the grid operator for providing hybridization of the electric grid, using the current market conditions. The amount of money one can expect to receive if one puts a HFCVs at the disposal of the grid operator is, in comparison to the hybrid HFCV and the BEV, significantly lower.

In the future increasing amounts of renewable energy will increase the price-differences for electricity and thereby for hydrogen, and thereby providing the foundation for more revenue from hybridization services. However the introduction of more and more electric vehicles (both BEVs, HFCVs and hybrid HFCVs) pulls in the other direction, and the vehicles will have to compete with other technologies such as heat pumps and flexible demand.

The findings are subject to the assumption about future technologies described in the report.

A. – INTRODUCTION, METHOLOGY & ANALYSIS MODEL

A.1 Glossary and terms, abbreviations and symbols

AAU	Aalborg University
AGC	Automatic Generation Control
BEV	Battery Electric Vehicle
CARB	California Air Resource Board
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DEA	Danish Energy Agency (Energistyrelsen)
DONG	Danish Oil and Natural Gas
EV	Electric Vehicle
FC	Fuel Cell
FCV	Fuel Cell vehicle
FOB	Free On Board
FPBEV	Full Performance Battery Electric Vehicle
FUDS	Federal Urban Drive Cycle
HEV	Hybrid Electric Vehicle
HFCV	Hydrogen Fuel Cell Vehicle
HT	High Temperature
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Changes
LCV	Light Commercial Vehicle
LFC	Load Frequency Control
LHV	Lower Heating Value
LT	Low Temperature
NEDC	New European Drive Cycle
PEMFC	Proton Exchange Membrane Fuel Cell
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State Of Charge
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
TSO	Transmission System Operator
TTW	Tank-To-Wheel
UCTE	Union for the Co-ordination of Transmission of Electricity
UPS	Uninterruptible Power Supply
WTW	Well-To-Wheel
WTT	Well-To-Tank

A.2 Project team

This project has been carried out as a research project supported by the ForskEL 2007 program from Energinet.dk.

The following organisations and individuals have acted as steering committee (SC) in the project:

- Strategic Analyst Per Sune Koustrup
- Assistant Professor Brian Vad Mathiesen, Aalborg University
- Business Development Manager Mikael Sloth, H2 Logic A/S
- Manager, Project department Kim Kjølhede, Dantherm Power A/S
- Portfolio manager Poul-Erik Skovsborg Hansen, Energimidt A/S
- Portfolio trainee Jesper Damtoft Andersen, Energimidt A/S
- Functional manager Kenn H. B. Frederiksen, Energimidt A/S
- Torben Fly Kristensen, Dantherm Power A/S
- Development manager Poul Lyhne, Vestforsyning
- Customer centre chief Ida Joel, Scanenergi A/S

The various SC members have contributed differently to the various parts in this report as shown below:

H2 Logic (chapter A.1, A.2, A.3, A.4.1, B.3.4, C.4, D.2 (except D.2.4) D.3, F.2, F.4, Appendix 1, 4, 5, 6)
H2 Logic + Aalborg University (main + co-author) (C.2.)
Aalborg University (B.1, B.2, C.1, C.3, F.3 (except F.3.8), Appendix 2, 3)
Aalborg University + H2 Logic (main + co-author)(A.4,, D.2.4, F.3.8)
Dantherm Power (D.1, E., F.1)
EnergiMidt (B.3)

The steering committee would hereby like to send their gratitude to the PSO steering committee for funding this project. Furthermore the steering committee would like to thank scientist Kaj Jørgensen DTU Risø for electric vehicles algorithms and Mogens Bjerg Mogensen from DTU Risø for discussions and information regarding Solid Oxide Electrolysers.

A.3 Introduction

The Intergovernmental Panel on Climate Changes (IPCC) estimate that the global CO_2-emissions have to be reduced by 50 – 85 %, compared to the year 2000 emissions, by 2050, and peak no later than 2015 if the global warming should be kept at 2,4° C or less.[1] The transport sector accounts for a large share of global CO_2 emissions and is the sector where CO_2 emissions rises the fastest and if global warming has to be slowed down emissions from the transport sector have to be dealt with. In 1999 there were approximately 730 million cars in the world, a number that is expected to increase to 2,8 - 4,5 billions by 2050.[2] If the transport sector are to reduce the CO_2 emissions by the same factor as other energy consuming sectors a reduction of between 87 and 97 % is needed.

Denmark was in 2008 the only EU country which was self-sufficient in oil and natural gas. However the Danish oil production peaked in 2004[3] and in 2005, the Danish gas production peaked.[4] It is by the Danish Energy Agency (DEA) expected that Denmark will be self-sufficient in oil till end of 2017, based on the contribution from reserves.[5] If the contributions from technological developments and exploration are included, Denmark is estimated to be self-sufficient in oil for approximately another 20 years. Denmark is expected to be self-sufficient in natural gas up to and including 2016, based on the contribution from reserves. For natural gas, DEA anticipates no significant contribution from technological developments because current technology has already generated a much higher recovery factor than for oil. Thus new energy sources and technologies are needed in order for Denmark to continue being energy independent.

Political plans in Denmark calls for increasing share of renewable energy, especially in terms of electricity from wind turbines. However wind power is a fluctuating energy source and the electricity production will inevitably become more fluctuating in the future. There will therefore be an increasing demand for electricity consumption that to a larger extent than today is able to follow these fluctuations. That is, deliver and receiving power and energy when there is a deficit and/or a surplus of power and energy.

The purpose of the analyses presented here is to provide information about the potentials of using electrolysers in energy systems with large amounts of intermittent renewable energy sources such as wind power. The electrolysers are combined with fuel cells in vehicles or stationary use but with emphasis on the vehicles. Different vehicles are analysed in respect to their ability to integrate renewable energy into the transport sector, improve fuel efficiency as well as the ability to integrate intermittent renewable energy sources. The socio-economic costs of the vehicles are also analysed.

The technologies are analysed in different future energy system designs, which reflect situations with significantly more wind power than in the current Danish energy system, and in an energy system going towards 100 per cent renewable energy. In 2012 the Danish wind power generating capacity is expected to have increased from the current 3,200 MW to approx. 4,120 MW, which will cover approx. 30 per cent of the final demand for electricity. This will pose significant challenges for the energy system.

The technologies analysed are hydrogen fuel cell vehicles (HFCV), plug-in hybrid hydrogen fuel cell vehicles (hybrid HFCV) and battery electric vehicles (BEV). For comparison future internal combustion engine petrol, diesel, biodiesel and bio-ethanol are included. Different configurations of the supply of hydrogen and electricity in plug-in vehicles have been analysed:

Hydrogen produced at electrolyser with hydrogen storage.
Hydrogen produced in electrolysers combined with plug-in battery with dump charge for hybrid hydrogen fuel cells vehicles.

Hydrogen produced in electrolysers with hydrogen storages combined with plug-in battery with smart charge for hybrid hydrogen fuel cells vehicles.
Hydrogen produced in electrolysers with hydrogen storages combined with plug-in battery with smart charge and possibility of vehicle to grid electricity for hybrid hydrogen fuel cells vehicles.
Plug-in battery with dump charge for battery electric vehicles.
Plug-in battery with smart charge for battery electric vehicles.
Plug-in battery with smart charge and possibility of vehicle to grid electricity for battery electric vehicles.

The project has consisted of the following work packages:

- WP1 – Project steering committee
- WP2 – Analysis of state-of-the-art and future prospects/targets for hydrogen & fuel cell power balancing concepts & technologies
- WP3 – Scenario development and impact analysis of hydrogen fuel cell power balancing concepts & technologies in the Danish energy system
- WP4 – Balancing power simulation and field tests with CanDan1 fuel cell units and hydrogen production plant
- WP5 - Business Case evaluation and description for various power balancing opportunities with fuel cells and hydrogen production plants
- WP6 – Recommendations, reporting and dissemination

A.4 Methodology and energy system analyses model

Three different organisations have analysed what the Danish Energy system might consist of for the years until 2050. One can therefore base the analyses' on assumptions from either the Danish Energy Agency, (DEA)[6], the Danish Wind Industry Association (conducted by EA analyse)[7] or The Danish Society of Engineers (Ingeniørforeningen i Danmark – IDA).[8]

The analyses from the Danish Energy Agency and the Danish Wind Industry Association are both partial analysis's, that is they both focus on off-shore windpower. The analysis from IDA is on the other hand an altruistic system analysis. Aalborg University (AAU) has contributed to the IDA report. The IDA report therefore seems to be a good starting point for the analysis's for the 2020 – 2050 timeframe. The chosen scenarios represent what the authors of this report believe to be realistic but yet ambitious scenarios. The scenarios are a mix of energy savings, more combined heat and power (CHP), a large fraction of energy crops and a large part of energy from, on- an off-shore windpower. In order to balance the increased quantities of fluctuating energy it is assumed that gradual grid reinforcements and expansions will find place as described in Nordic Grid Master Plan 2008.[9]

It is assumed that hydrogen will only be produced from renewable sources. Another realistic scenario in a Danish context is hydrogen produced from natural gas. This possibility won't be analysed of a number of reasons:

1) The price of natural gas is increasing rapidly these years whereas the price on electricity based on wind power is still decreasing as a function of technological progresses and economics of scale
2) The Danish gas production peaked in 2005[10] and it is expected that Denmark will become a net importer after 2016.[11] For energy security and trade balance reasons one shouldn't increase the use of natural gas
3) If the combined Danish CO_2 emissions have to drop significantly hydrogen has to be produced on CO_2 neutral sources. Carbon capture and storage (CCS) is very energy intensive, costly and yet not commercial available.
4) More wind power equals – ceterus paribus - a larger need for balancing power. Hydrogen produced on the basis of wind power can provide this.
5) The purpose of this report is to analyse the balancing potential of hydrogen produced from fluctuating (wind)power

The consortium and the contracting authority (Energinet.dk) want to analyse ambitious yet realistic levels for production and usage of hydrogen and fuel cells. It is the task of the consortium to analyse what can be achieved by a progressive approach.

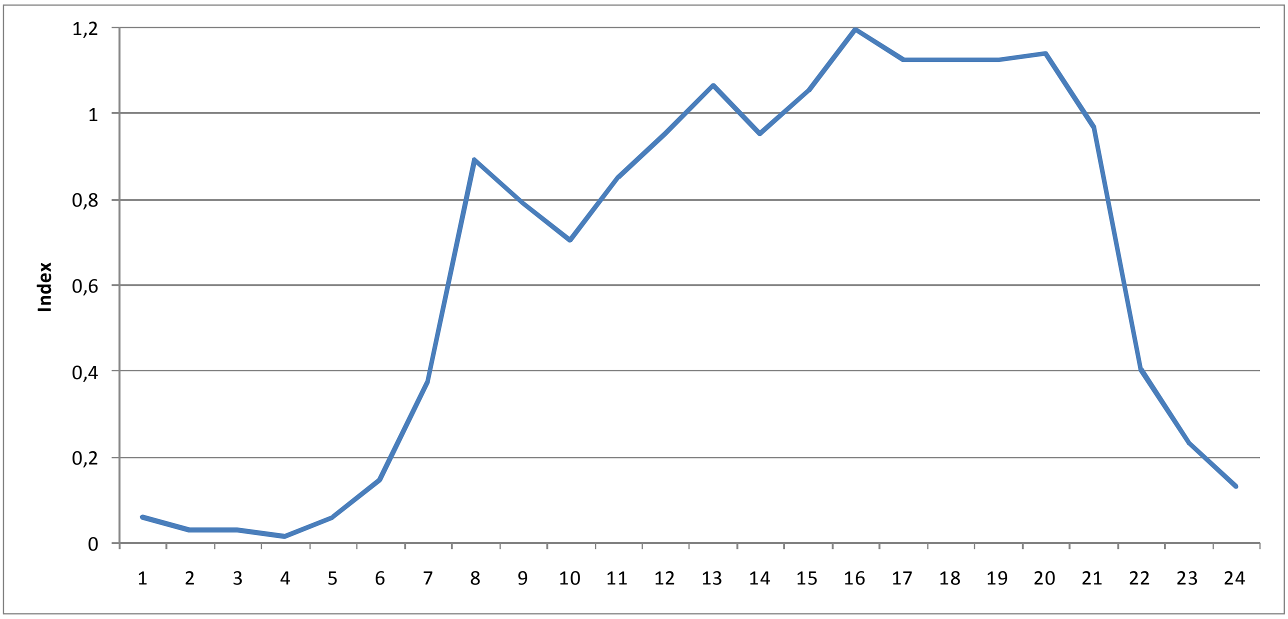
In the first part of the analyses the scenarios are defined. Secondly the energy system analyses model used is presented. In the analyses the ability of electrolysers in combination with fuel cells to improve the overall system fuel efficiency is analysed for different types of vehicles as well as the ability to integrate fluctuating intermittent renewable energy sources. In the technical energy system analyses the changes in CO_2-emissions of using these technologies is analysed.

In the second part, the socio-economic effects of fuel cells and electrolysers are analysed. In these market analyses the operation of the plants installed optimises their operation according to their marginal operation costs considering the electricity demand from vehicles. The analyses of the technologies are also related to the current market configuration (spot-market and power regulating market), and to historic data for these markets. Such analyses can reveal the potential of the technologies to have positive socio-economic effects. The costs of the different technologies are also coupled to the technical energy system analyses.

New data for future high temperature Solid Electrolysers (SOEC) have been gathered and data sets for a Battery Electric Vehicle (BEV), a plug-in Hybrid Electric Vehicle (plug-in HEV) and a Plug in Hybrid Hydrogen Fuel Cell Vehicle (Plug-in HFCV) has been constructed. These data are used as input in the analyses here.

As the first step, the transport scenarios are presented, i.e. the combination of fuel supply with different types of vehicles. Next the energy systems in which the transport scenarios are analysed are defined, as are the fuel and fuel handling costs. On this basis the energy system analyses model can be used in order to analyse the transport scenarios from different aspects. The distribution of the transport demand is based on data from the United States used in previous analyses of battery electric vehicles.[12] The distribution for a typical day of transport demand is presented in Figure 1.

Figure 1 – Typical transport demand for one day used in the analyses

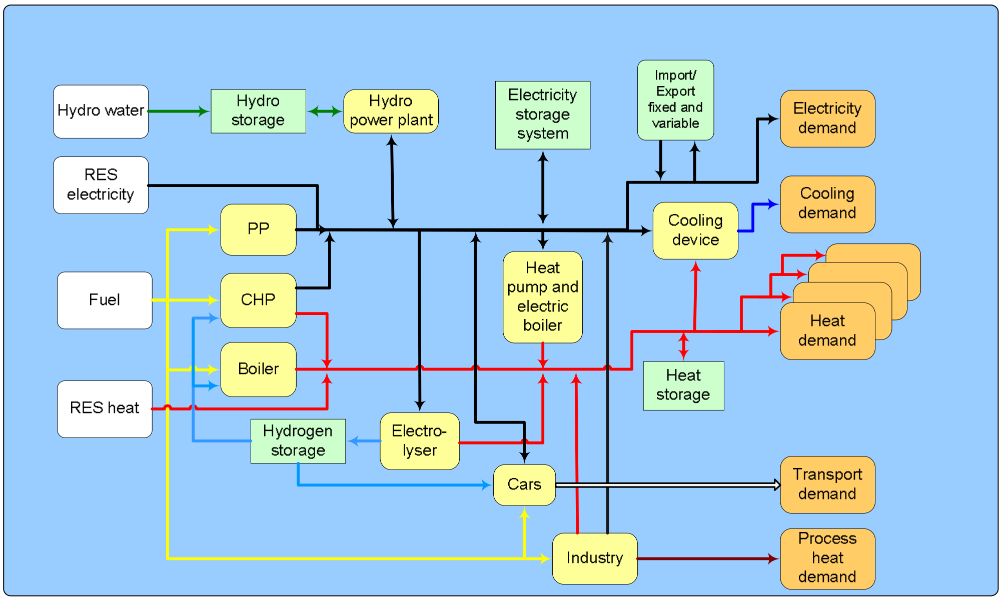


In this report, the energy system analysis and planning model EnergyPLAN is used.[13] The main purpose of the model is to facilitate the design of national energy planning strategies on the basis of analyses of technical and economic consequences of different energy system designs or investments in new technologies for electricity and heat production as well as for transport. The model can identify potential excess electricity amounts and distributions over time. The model can analyse the consequences of technologies able to utilise such excess production.

The model includes regulation strategies and analyses the interaction between CHP, and fluctuating renewable energy sources in steps of one hour throughout one year. The model is an input/output model and general inputs are demands, renewable energy sources, energy plant capacities, costs, and a number of optional regulation strategies emphasising import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, CO_2 emissions, import/exports, and total costs including income from the international exchange of electricity.

In Figure 2 the principle units that can be analysed is illustrated. Documentation can be found at www.energyplan.eu. The model is free for use and for download.

Figure 2 - Principle relations between the elements in the energy system in EnergyPLAN model



In technical energy system analysis the effects on fuel efficiency and the ability of the transport scenarios to integrate intermittent renewable energy are analysed as well as the resulting CO_2-emissions. In the technical energy system analyses, inputs include energy demands, production capacities and efficiencies.

In the technical energy system analyses the electrolysers produce at time with excess electricity production, wind production or CHP production if possible. If the hydrogen storages are present, these are used to optimise hydrogen production according to this strategy.

For the combinations of hydrogen fuel cell vehicles with batteries in hybrid hydrogen fuel cell vehicles and for battery electric vehicles, the following loads strategies apply. For dump charge, the vehicles are charged evenly in the periods they are parked, disregarding the production at e.g. wind turbines and without large hydrogen storages. If smart charge is possible, the vehicles are charged at times with excess electricity, wind power or CHP production if possible, using the charger capacity, the hydrogen storage or batteries in the vehicles. In the vehicles to grid solutions (V2G), the smart charge strategy is combined with an ability to replace production at power plants (PP) with electricity from batteries.

In the market-economic-optimisation-strategy-analyses further inputs are needed in order to determine marginal production costs, such as variable operations and maintenance costs (O&M), fuel costs and CO_2 emission costs. This modelling is based on the assumption that plants optimise according to business-economic profits, including current taxes. Output consists of annual energy balances, fuel consumptions and CO_2 emissions, fuel costs, etc.

In the market economic optimisation hydrogen production is placed at times with the lowest electricity costs, using the capacity of the electrolysers and the hydrogen storage if present. With smart charge the vehicles are charged at times with the lowest possible costs. The V2G solution is used for selling electricity at times when prices are high enough for this solution to make economical sense.

The technical and market-economic analyses can be conducted under different regulation strategies, i.e. in closed or open systems or with different regulations of CHP plants and critical excess electricity production as well as ancillary service designs, etc.

The transport scenarios are analysed in the different energy systems using both open and closed energy system analyses. In closed technical or market optimisation energy system analyses, the total fuel consumption, excess electricity from wind turbines, CO_2-emissions and total socio-economic costs. The total socio-economic costs require further inputs of investment costs, the fixed O&M and lifetimes.

In open energy systems the ability of the transport scenarios ability to profit from electricity exchange is analysed in the different energy systems. Here the ability to trade and exchange electricity on international markets and according to prices is analysed. Such analyses can reveal the flexibility of technologies, when large amounts of intermittent electricity are produced. Additional inputs are different external electricity market prices as well as the data needed in order to determine marginal production costs of the electricity production presented above. Further inputs are market price distributions and a price dependency factor, which are applied in order to determine the response of the market prices to changes in production or demand, and import or export. Hence, the ability to profit from exchanges can be identified.[14] The modelling is based on the assumption that plants optimise according to business-economic profits, including current taxes. These analyses are performed in an open energy system with international electricity trade and are compared to a market-economic optimisation of a closed system. This enables the identification of the net earnings made on electricity trade for the different transport solutions. The results represent the socio-economic profits of electricity trade, excluding taxes.

In combination with the analyses of the different transport scenarios in different energy systems and with different fuel costs, key parameters are investigated in sensitivity analyses. These analyses are used to further substantiate the conclusions.

A.4.1 Energy-chain analysis structure

When using energy from the electricity grid the energy chain can be divided in to main parts - a grid-to-tank (GTT) and a tank-to-wheel (TTW) part. This division is used in this report.

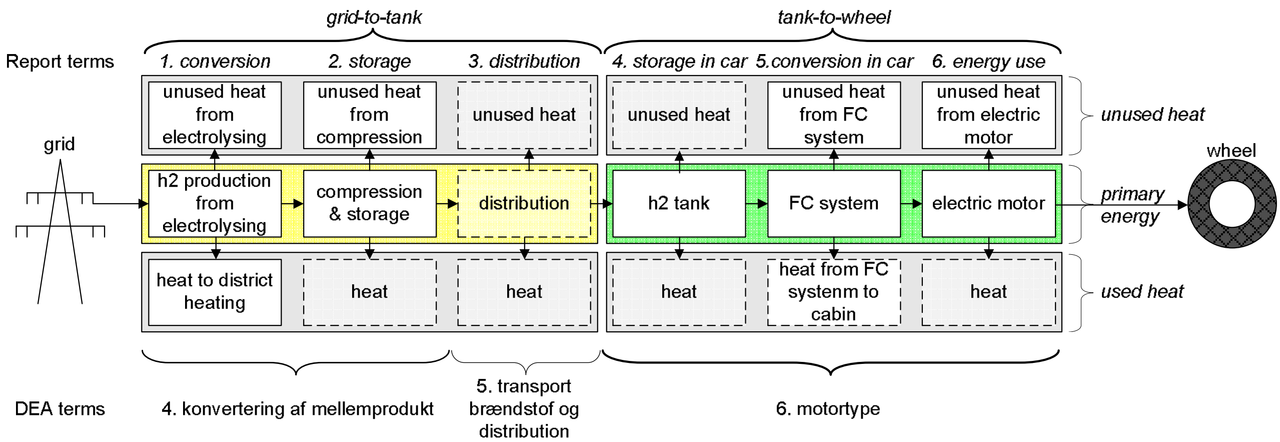
The structure and terms used in "Alternative drivmidler i transportsektoren - COWI beregningsmodel" are used as a starting point for this chapter[15] (for further description see appendix 1). Some of the terms have been changed and some have been split up. The reasons why it has been decided to split up more of the DEA terms/steps are that it increases the transparency in the analysis', it makes it easier to make continuous improvements as better technologies emerge. Finally this methodology is in better accordance with international well-to-wheel studies.

The analysed grid-to-wheel energy chain for hydrogen is seen in the figure below. For the hydrogen energy-chain step 3. distribution can be eliminated if the hydrogen is produced on-site. Furthermore more steps can be added for the hydrogen-chain if one uses e.g. low pressure distribution by pipeline combined with on-site compression. Therefore the energy-chain shown below is just one of many possible hydrogen energy chains. It is however by the authors regarded as the shortest and most energy-efficient zero emission hydrogen chain, where hydrogen is produced on electrolysers.

At each step a closed-energy-analysis is conducted. Since energy can neither emerge nor disappear the energy at each step has to summarize to 1 (equal to 100 per cent). The energy at each step is divided into primary energy, secondary energy and tertiary energy. The primary energy is the energy which is normally analysed in energy-chain-analyses and are in this report either hydrogen or electricity. Primary energy can either directly or at a later energy-state conduct work. There are heat that can be harvested in one form or another. In this report the term "useful heat" or "used haet" is used. Useful heat is in this report either used in district heating or for heating up the cabin in vehicles. An advantage of conduction this kind of analysis is that is becomes clear where the biggest improvements in energy-chain efficiency can be obtained with the least work. Finally there is "waste heat" or "unused heat".

In the figure below the hydrogen energy-chain are shown.

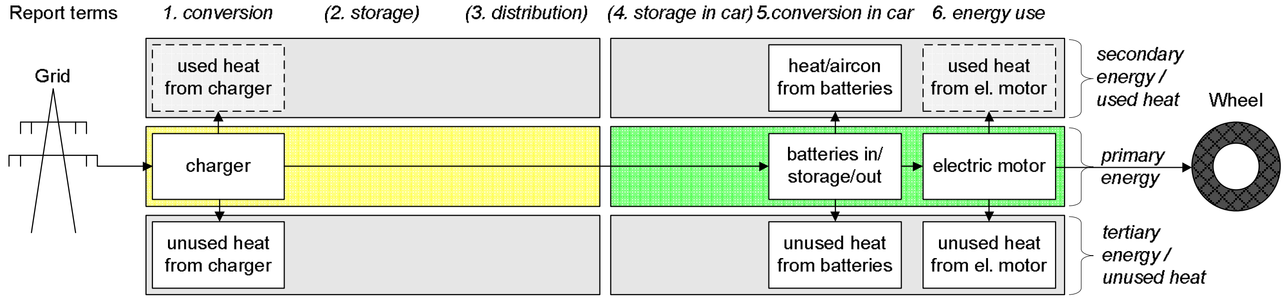
Figure 3 – The hydrogen energy-chain from grid-to-wheel



When analysing stationary power the report terms "4. storage in car" are changed to "4. storage at stationary power unit". The methodology is the same.

In the figure below the battery energy-chain are shown.

Figure 4 – The battery energy-chain from grid-to-wheel



There are energy losses in the batteries when charging, in the batteries when they are not used and when they are discharged. Since these losses are rather small in state-of-the art batteries these three steps have been gathered in one step (see step 5. conversion in car in the above figure).

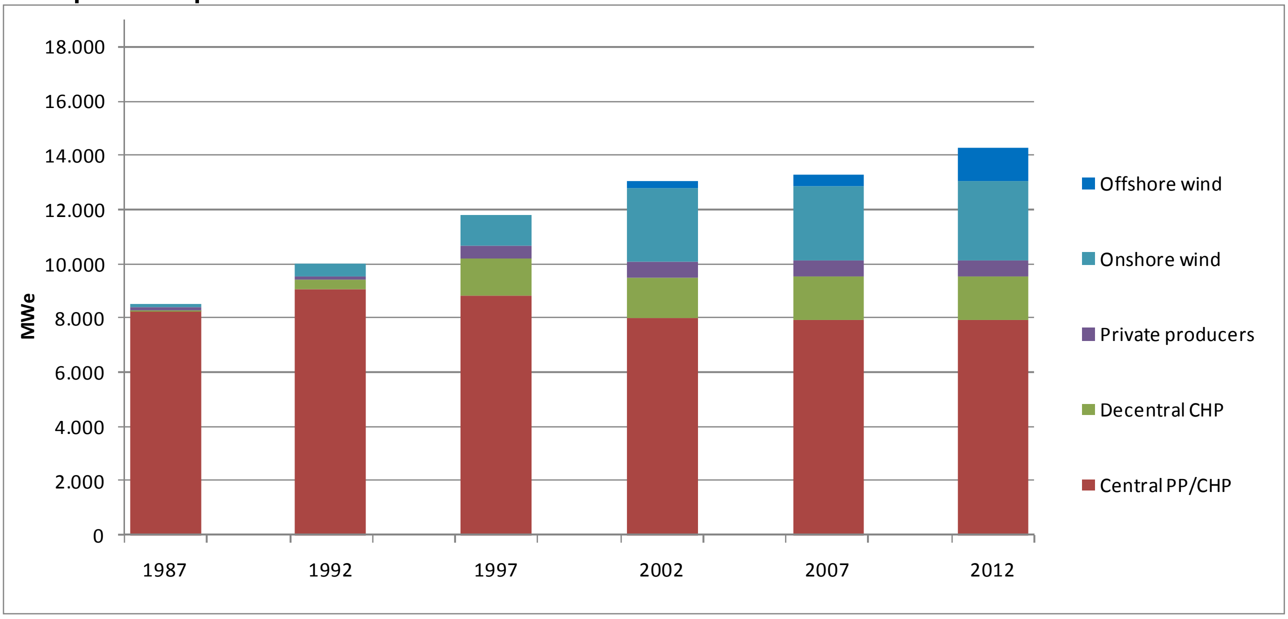
Regenerating is not included in the above figures for either hydrogen or battery.

B. – THE ENERGY SYSTEM ANALYSED

B.1 The energy systems analysed

For the analyses here, significantly more intermittent renewable energy is introduced. The current wind power capacity is 3.149 MW installed at 5.200 different locations, which supply approx. 20 per cent of the electricity demand.[16][17] 2.200 MW is small distributed CHP plants or industrial production plants located at more than 700 different locations, of which more than 650 are smaller than 10 MW.[18] In addition the system also includes 17 central power plants (PP) and CHP plants with a total capacity of 7.968 MW. In 1987 the energy system was a classical centralised system with very few plants. This has changed significantly over the last 20 years. In 2012, the total wind power installed is planned to be 4.124 MW, as offshore wind power is planned to increase from 423 MW in 2008 to 1.223 MW in 2012 and onshore wind power is planned to increase by 175 MW in the same period. In Figure 5, the development of the installed capacities is illustrated as well as the expected situation in 2012.

Figure 5 – Power generation capacities in the Danish energy system from 1987 to 2007 and anticipated capacities 2012



B.1.1 The reference energy system

For the purpose of the technical and socio-economic analyses different energy systems are constructed. As the point of departure the Danish energy system for 2006 is used.[19] This system is reconstructed in the EnergyPLAN model based on the corrected gross energy production for 2006 and including electricity export. In the Energy Statistics 2006 the import and the export are higher than in the results in the model, however, as the fuel consumptions are the same, the 2006 reference system is a good point of departure for the analyses. This reference energy system has also been used in Ramboll, 2008.[20]

B.1.2 Towards the 100 per cent renewable energy scenario

The purpose of the analyses here is to investigate electrolysers and fuel cells in energy systems with more renewable energy than today. From the 2006 reference energy system, energy systems for 2012, 2030 and 2050 is modelled with the last energy system based on 100 per cent renewable energy in 2050. Such a transition requires significant amounts of renewable energy as well as improvements in the efficiencies of conversion technologies and savings in the end demand.[21][22] The initiatives taken below have all been analysed elsewhere. Such inputs are used in order to analyse the ability of fuel cells and electrolysers to balance the system.[23][24][25] The changes in the energy systems are based on the assumption that such savings and new production technologies can be implemented gradually as worn out plants etc. are replaced or subject to maintenance.

Wind power energy production is increased from 6,11 TWh in 2006 to 11,56 TWh in 2012 in the business-as-usual (BAU) energy system for 2012. The production from the 2.900 MW onshore turbines produce 6,79 TWh corresponding to a normal wind year. The off-shore wind turbines produce 4,77 TWh. The present energy system is used in combination with a total of 4.124 MW wind power for the 2012 system. In the 2006 system the wind power production was marginally lower than a normal year. For wind power 50 per cent of the electricity demand is covered in 2030- Towards 2050 the wind power is increased to 75 per cent of the demand in 2050 by expanding off-shore wind power to 19,07 TWh. This corresponds to 2.900 MW on-shore and 3.150 MW off-shore.

Electricity savings are introduced corresponding to 30 per cent of the total 2006 demand in 2050. Such saving may be placed in both households and commercial activities. The savings introduced are based on the IDA Energy Plan 2030.[26]

The **space heat savings** introduced exclude the demand for hot water, which corresponds to approx. 15 per cent of the final demand in 2006. In 2050 75 per cent heat savings are implemented. The heat savings are introduced both in and outside district heating areas. In district heating areas the grid losses are included. Such losses in combination with savings in space heating is investigated in Ramboll, 2008.[27], which is used in the energy system scenarios constructed here. No expansion of the district heating system is included, as suggested Ramboll, 2008.[28] Although such efforts would be feasible, this is not the focus here. These savings change the annual distribution of the heat demand, and especially reduce the peak demands.

The **efficiency** of power plants and CHP is increased gradually from 2006 to 2050. The increases in the average efficiency are based on implementing better technologies such as solid oxide fuel cells, combined cycle gas turbines etc. and decommissioning plants with rather low efficiencies. This also implies that the amounts of gaseous fuels are expanded gradually to 100 per cent in the heat and power sector in 2050, such as syngases or biogas derived from biomass. In the mid-term 2030 system natural gas may also play an important role in this system.

Table 1 – Steps towards a 100 % renewable energy system in 2050

Energy systems	Reference 2006	BAU 2012	Target 2030	Target 2050
Wind power (% of demand)	17%	32%	50%	75%
Electricity savings	-	0%	10%	30%
Space heat savings (excl. hot water)	-	0%	50%	75%
Savings in fuels for industry	-	-	15%	30%
Efficiency of power plants	39%	39%	50%	60%
Efficiency of CHP (electricity/heat)	35%/48%	35%/48%	40%/50%	50%/40%

The steps and changes introduced above only takes into account the heat and power sector. In the analyses here the following changes are also included in the 2050 energy system:

- Industrial fuel consumption is reduces by 30 per cent and replaced by biomass.
- Fuel consumption for the oil and natural gas extraction in the North Sea is not included.
- No changes have been made to the heat and power capacity installed in 2006 other than for wind power.

Un-flexible waste incineration CHP is maintained at the 2006 distribution and amount, but in 2050 the fossil part of the waste is assumed to be replaced by biomass, which removes the last fossil CO_2-emissions from the 2050 system.
Fuel for transport, incl. aviation is assumed to be replaced by biomass 1:1. Such a transition may be the result of limiting the growth in the transport demand while having more efficient vehicles.
All individual heating systems are replaced by biomass boilers and 30 per cent is covered by solar thermal.

The 100 per cent renewable energy system represents one such system, but no efforts has been made to optimise the different parts and interaction in such a system here. It should be noted that here the 100 per cent renewable energy system is introduced with no efforts made in order to create a flexible energy system that can integrate wind power. In reality efforts should be made to integrate large and small heat pumps, flexible demands, electric vehicles etc. The reason for this is to enable a systematic analysis of electrolysers for balancing fluctuating renewable energy.

In the analyses of transport technologies the only transport demands included are 500.000 vehicles for each technology.

B.2 Costs of fuels, fuel handling, electricity and CO_2 quotas

The main assumption in the analyses is that the oil prices will not be constantly high or low but will continue to fluctuate. Three different sets of future fuel prices are related to the oil prices. The three price ranges are listed inTable 2. The base line level represent fuel prices from the spring/summer 2008 equivalent to an oil price of 120 $/bbl at a dollar exchange rate at 4.8 DKK/$. The lower price level is based on the assumptions recommended by the Danish Energy Authority in February 2008.[29] For wood pellets, though, the price level expected by the Danish Energy Authority is used as the base line, and the current price is at the lower level. The high fuel price level is calculated by adding the difference between the lower and the current fuel price level to the base line assumptions.

Natural gas prices are based on crude oil prices by assuming a 62 per cent relation to the oil price, while for fuel oil, the relation is 70 per cent. For all biomass resources, straw costs are used for fuels in central and local plants, while wood pellet costs are used for biomass fuel costs in households. Please note that biomass-based fuels are also assumed to fluctuate in the analyses. The fuel transport and handling costs used are derived from the Danish Energy Authority and listed in Table 3. The equivalent oil prices are adjusted to reflect 6.6 DKK/bbl.

Table 2 – Fuel costs depending on oil price per barrel (bbl)

	DKK/GJ [1]	Crude oil	Coal	Natural gas	Fuel Oil	Gas oil / Diesel	Petrol / JP	Straw	Wood pellets
Low	47 $/bbl	51,0	13,4	31,6	35,7	63,7	67,8	24,7	48,4
Medium	87 $/bbl	98,6	24,6	61,2	69,0	123,3	131,2	36,2	59,9
High	129 $/bbl	146,3	35,7	90,7	102,4	182,9	194,6	47,7	71,4

Table 3 – Fuel transport and handling costs per GJ

DKK/GJ	Coal	Natural Gas	Fuel Oil	Gas oil Diesel	Petrol JP	Straw	Wood pellets
Power Stations (central)	0,50	3,20	1,70			12,1	
Distributed CHP, district heating & Industry		7,80	14,00			8,1	
Individual households		19,60		21,30			44,6
Road transport				23,10	31,20		
Airplanes					5,10		

Using the rather high fuel costs from the spring/summer of 2008 as the base line reflects the latest World Energy Outlook from the International Energy Agency (IEA) in 2008 in which an oil price of 122 $/bbl is anticipated in 2030. This forecast has now been adopted by the Danish Energy Authority and reflects fuel prices between the base line and high fuel prices.[30]

The socio-economic feasibility study does not include externalities, i.e. environmental or health effects, etc. CO_2 quota costs are included in the analyses; however, this does not reflect the externality costs of the emissions. In accordance with the recommendations of the Danish Energy Authority, a long-term price of 175 DKK/ton is used here, although this level may prove conservative in a future with higher international emission reduction targets. A socio-economic interest rate of 3 per cent is used in the analysis.

[1] The dollar exchange rate used is 6.6 DKK/bbl. With the lower exchange rate of 4,8 $/bbl, the oil prices levels corresponds to 62, 120 and 178 $/bbl respectively.

For the electricity market exchange analyses, estimates of long-term electricity costs are required. The long-term Nord Pool electricity prices recommended by the Danish Energy Authority are used as a reference price scenario.[31] The annual average price is expected to be 367 DKK/MWh, which is used here in combination with the hour-by-hour fluctuations on the Nordic electricity market in 2005. The 2005 price fluctuations reflect a normal year regarding the contents in the Norwegian water reservoirs. CO_2 quotas are assumed to have a constant effect on the prices, corresponding to 70 DKK; thus, 297 DKK/MWh are expected to fluctuate.

Each type of plant is expected to produce electricity according to its business-economic marginal costs including handling costs and taxes. In the results, taxes are excluded, hence representing socio-economic costs. Prices on the electricity markets become zero in the model in extreme wind situations.

In the Nordic electricity system, prices depend heavily on the water content in the Norwegian water reservoirs. Variations typically occur in cycles of seven years with one dry year, three normal years and three wet years.[32] These variations as well as doubling the CO_2-costs and the interest rates are included in the sensitivity analyses.

In the market exchange analyses 2.500 MW interconnectors are used in the analyses as the capacity used for international trade. 5.000 MW has been included in a sensitivity analyses.

B.3 The balancing market in West-Denmark

Denmark is divided into two separate power areas, which since 1st of January 2005 has been managed by the Danish TSO (Transmission System Operator) Energinet.dk. The main tasks of Energinet.dk is 1) managing and securing the daily electricity flow within as well as to and from the two areas and 2) securing that the Danish electricity demand also in the future will be well supplied.[33] In order to secure the daily flow of electricity within West-Denmark Energinet.dk has several possibilities at hand[34]:

1) Primary reserves (Primary Control): local automatic control which delivers reserve power in opposition to any frequency change
2) Regulation (Secondary Control): Regulation, also referred to as automatic generation control (AGC) or load frequency control (LFC) is used to fine-tune the frequency and voltage of the grid by matching generation to load demand (In Denmark within *one* minute).[2]
3) Spinning reserves (Tertiary Control): Spinning reserves refers to additional generating capacity that can provide power quickly (In Denmark within 15 min) upon request from the TSO. Generators providing spinning reserves run at low or partial speed and thus are already synchronized to the grid.

B.3.1 Primary reserves

Primary reserves (+/- 32 MW) *(Primary Control)*: Primary reserves are automatic production- or consumption-units, which by way of automatic generation controls keeping a constant frequency of 50 Hz.[35] Primary controls are supervised by all TSO's within the UCTE-area (Union for the Co-ordination of Transmission of Electricity) controlling/supervising 3000 MW. Energinet.dk is required to deliver a pro rata amount of MW compared to the amount of production facilities in both the Western and the Eastern part of Denmark. Technically primary reserves should be delivered at frequency disruptions of up to +/- 200 mHz (0,2 Hz) compared to the reference of 50 Hz. The reserve should be delivered linearly and completely activated within 30 seconds. The regulation should be running for at least 15 minutes or until the Regulation or Spinning reserves takes over. After running the reserve should be reestablished within 15 minutes. Availability payment in Western Denmark in July and August 2008 was between 274.429 and 1.358.095 DKK/MW/Month respectively with the capacity of 4 - 26 MW.[36] Since the average price over a year is not known an average of July and August 2008 is used. An average price of 816.262 DKK/MW-month is used. This price is equal to 1,10 DKK/KW-h.

B.3.2 Regulation

Regulation (+/- 140 MW)[3] *(Secondary Control)*: During periods of larger electricity disruptions the or Load Frequancy Control (LFC) and Automatic Generation Control (AGC) is used to fine-tune the frequency and voltage of the grid following the primary reserves have stabilized the frequency. LFC is an automatic up- and down regulating reserve, which is running until a balance has been obtained or until the spinning reserves are ready for controlling the balance. The LFC is required to: A) Be completely activated 30 seconds after the activation order and B) Regulate with an effect gradientof at least 10% of the offered up-/down regulation reserve pr. minute. Availability payment in Western Denmark in July and August 2008 was between 114.982 and 440.232 DKK/MW-month for capacities of +/- 40 to +/- 90 MW[5]. An average price of 277.607 DKK/MW-month is used. This price is equal to 0,37 DKK/KW-h.

[2] Regulation must be under direct real-time control (automatic) of the grid operator, with the generating unit capable of receiving signals from the grid operator's computer and responding within a minute or less by increasing or decreasing the output of the generator.

B.3.3 Spinning reserves

Spinning reserves (+ 630 MW / - 160 MW) [3] *(Tertiary Control)*: The requirements for supplying regulating-power in the Danish power grid is as follows: A) Bids can be entered for a minimum of 10 MW and a maximum of 50 MW (bundling); B) The amount of MW-power offered must be constant during the entire period offered C) The player must be able to fully activate a given bid within maximum 15 minutes from receipt of the activation order. Kempton[37] use the term "spinning reserves" the same way as described above.

A player who wants to make spinning reserves available for the TSO can join by one of three different models: 1) The player can conclude an (e.g. monthly) agreement with Energinet.dk committing the player to entering bids for a specified volume over a specified period of time. On activation (regulating power market) the player receives in return an availability payment in excess of the energy payment. 2) The player can refrain from concluding such an agreement, instead by entering regulating-power bids as the player sees fit. On activation, the player is not entitled to any availability payment in excess of the energy payment. 3) The player can enter the spot market as he sees fit without any constraints about when to supply power. The spot prices are less attractive compared to the regulating-power market.

The daily procedure of the registration of bids, handling the activation order from the TSO and the final settlement is handled by the balance responsible party. The bid-prices should be submitted according to the following: *Up-regulating price* => Spot-price and *Down-regulating price* <= Spot-price. For every hour the price is settled according to the principle of marginal price. It is the sum of activated bids on the NOIS (Nordic Operational Information System) list that determines the overall situation in a given hour, consequently, it is not the local demand that determines the direction of the regulation but the aggregated net regulation carried out in the Nordic area. Finally, orders for upward or downward regulation are communicated either on the basis of power schedules at five minute intervals sent to the balance responsible party by Energinet.dk (Denmark West) or by direct activation without any exchange of schedules (Denmark East).

The availability payment for West-Denmark from 1st January – 31st August 2008 was on average 38,37 DKK/MW (61,14 DKK/MW in peak hours and 24,13 DKK/MW in off-peak hours) for up-regulation in 2570 hours (989 peak hours and 1581 off-peak hours) and an average of about 35,34 DKK/MW (0 DKK/MW in peak hours and 57,14 DKK/MW in off-peak hours) for down-regulation in 1932 hours (737 peak and 1195 off-peak hours).

The energy payment for West-Denmark from 1st January – 31st August 2008 has an average of 527,38 DKK/MWh (634,05 DKK/MWh in peak hours and 460,66 DKK/MWh in off-peak hours) for up-regulation in 2570 hours (989 peak hours and 1581 off-peak hours) and an average of about 281,97 DKK/MW (333,45 DKK/MW in peak hours and 250,23 DKK/MW in off-peak hours) for down-regulation in 1913 hours (737 peak and 1176 off-peak hours).

Table 4 – Overview of the balancing market in west-Denmark

	Number of MW	DKK/MW-month	Hrs/yr	1.000 DKK/yr
Primary reserve (Automatic controlled frequency to 50 Hz)	+/- 32 MW	274.429 – 1.358.095	Unknown (availability payment)	105.381 – 521.508 (313.446)
Secondary reserve (AGC / LFC)	+/- 140 MW	114.982 - 440.232	Unknown (Availability payment)	193.170 – 739.590 (466.380)
Tertiary reserve (Spinning reserve)	+ 630 MW / - 160 MW	Availability payment (Average in 2008): Upreg.: 38.37 Downreg.: 35.34	Upreg.: 2.570 hrs Downreg.: 1.932 hrs	Upreg.: 62.125 Downreg.:10.924
		Energy payment (Average in 2008): Upreg.: 527.38 Downreg.: 281.97	Upreg.: 2.570 hrs Downreg.: 1.913 hrs	Upreg.: 853.881 Downreg.: 86.305
Combined				1.311.786 – 2.274.333 (1.793.061)

Source:[38]

Estimated marketsize is between 1,3 and 2,3 billion DKK/yr in West Denmark. The average estimated markedsize is 1.778 mio. DKK (1,8 billion DKK).

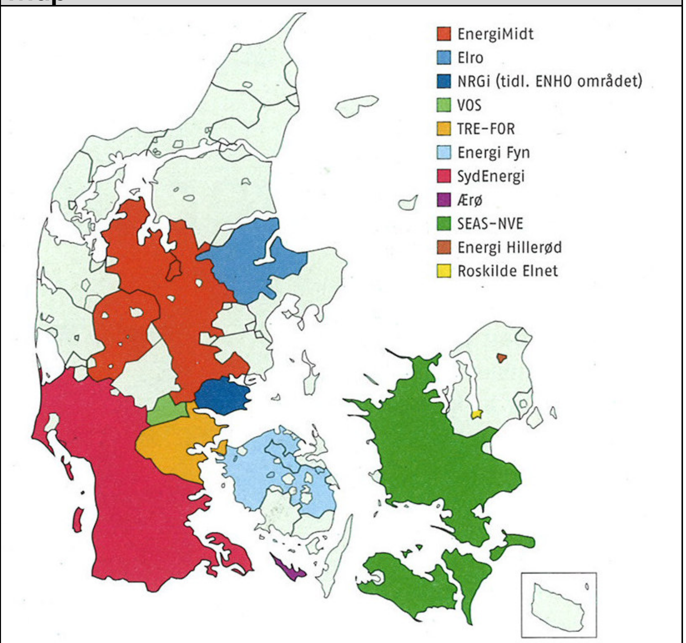
B.3.4 Smart meters

Approximately half of the Danish electricity consumption is used by consumers who use more than 100.000 kWh/yr.[39] Consumers who use more than 100.000 kWh/yr can already buy electricity on an hourly basis. Smart meters are mandatory for consumers using more than 100.000 kWh/yr. Private consumers and smaller business with a yearly consumption of less than 100.000 kWh on the other hand, have so far paid an uniform price pr. KWh electricity.

If the private consumer in the future wants to charge an electric car during nighttimes, or at other times when the electricity price is low, it is a necessity that he/she has a smart meter. Otherwise the customer and the electricity distribution company don't know how much electricity the single consumer is using when prices are low and high.

Many electricity distributors in Denmark have already installed, or are at the moment installing, smart meters at their private customers (see Table 1 below). 1.26 mio. smart meters are installed or planned installed as of November 2008. Most of these will be installed before 2011. It is estimated that another 1.97 mio. smart meters are required in order to have a 100 % coverage in Denmark.[40]

Table 5 – Existing and planned smart meters in Denmark

Company	# smart meters	Map[41]
EnergiMidt	147.000	
Elro	50.700	
NRGi	152.800	
VOS	5.100	
TRE-FOR	130.700	
Energi-Fyn (incl. Odense Energi)	158.100	
SydEnergi	262.100	
Ærø	5.300	
SEAS-NVE	354.500	
Energi Hillerød	58.000	
Roskilde Elnet		
Odense Energi	74.000	
Existing and planned measures	1.266.300	
Total number of measuring points	3.236.300	
Remaining	1.970.000	

Smart meters from different companies might use different communication protocols. Since no dominant design and no Danish and/or international standard exists some smart meters might not comply with the future communication needs. This subject has to be further investigated. In the analysis it is assumed that all BEV, plug-in HEV, HFCV and plug-in hybrid HFCV comply with the standards of the future.

According to Dansk Energi[42] smart meters costs an average of 181,7 Euro pr. smart meter. EnergiMidt e.g. expects an expenditure of appr. 200 mio. DKK for 172.000 installations.[43] It is based on a price of 181,7 Euro/smart meter estimated that the remaining 1.97 mio. smart meters will cost 2,67 billion DKK.[3]

[3] Own calculations.

C. – GRID-TO-TANK

The purpose of the analyses here is to investigate the integration of intermittent renewable energy using electrolysers and fuel cells, hence it is assumed that hydrogen is produced with electrolysers.

A framework for the analysis of energy from electricity grid to tank is set up. Within the framework electrolysers, compression, storage and refuelling of hydrogen are described.

C.1 Hydrogen production from electrolysis

Hydrogen can be produced from a broad range of different sources. As of 2008 more than 95 % of hydrogen produced worldwide origin form fossil fuels, (of which natural gas reforming is the most important) and less than 5 % of worldwide hydrogen production origins from electrolysis. Alkaline technology is analysed as of 2008 and SOEC is analysed in the 2020, 2030 and 2050 timeframe, since SOEC is expected to be more efficient and more durable and is expected/assumed to be commercial ready by 2020. On only onsite production is analysed in this report.

Most of the forecasted hydrogen production is expected to be used in plug-in hybrid HFCVs. These vehicles are expected to run primarily on electricity from batteries on trips less than 50 – 60 km and on hydrogen on trips longer than 50 – 60 km.

C.1.1 Alkaline electrolyser

Alkali electrolysers are already well developed and have been used for several decades in the chemical and metallurgic industry and for production of fertilizer in the form of ammonia (NH3). No significant technological improvements are expected, however large price reductions may be secured when using the technology for production of hydrogen as transport fuel due to potential higher volumes.

The data listed here is based on state-of-the art atmospheric pressure alkaline electrolysers from StatoilHydro. Plants are either operated at atmospheric pressure, or with pressurised operation between 4 and 30 bar.

The cost of alkaline electrolysers is heavily dependent on the size of the plant. In this analysis only large scale production plants are included, where the costs from the Danish Energy Authority[44] is used for large scale plants (>2 MWe). The costs are estimated to be at least 0.2 M€/MW with fixed O&M costs of 3 per cent of the initial investment. The lifetime is 20 years with major services every 6 years.

The start-up time of current large scale alkaline electrolysers is approx. 2 hour to 100 per cent and they are not designed for fast regulation abilities, however downward regulation can be achieved within a few seconds.. Regulating up and down tears the cells whereas turning the stack on or off does not affect the lifetime of the cells significantly. The stacks often have the maximum lifetime (in hrs) when used at 80 – 90 % of their maximum capacity.

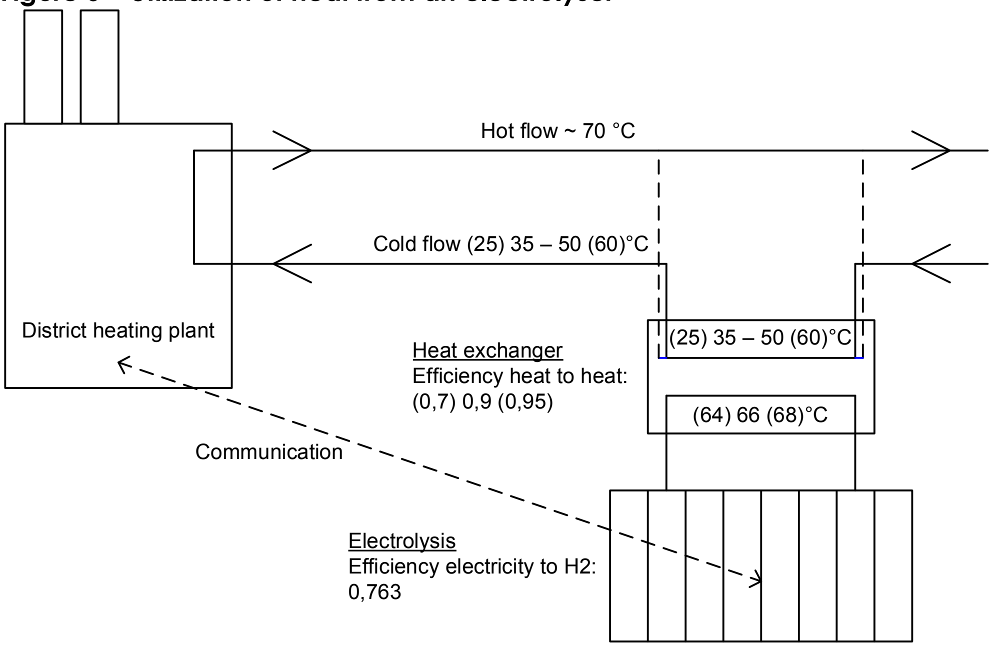
The efficiency of alkaline electrolysers can be very high, however this would increase the costs significantly as the current density would be lowered.

The LHV for alkaline electrolysers has been calculated by converting from 71-75 per cent based on the HHV to the LHV and adding 5 percent losses in the inverter.[45] The same LHV occurs if calculated from the cell current density of 1.3 V for SOEC to 1.8 V for alkaline electrolysers combined with inverters. The LHV for commercially available technology is confirmed in the CONCAWE project from march 2007.[46]

The current cost for a 43 nm3/hr electrolyser without any compression, purifying etc. is 1,26 M€/MW capacity (at 7,45 DKK/Euro). This price as of 2008 with the current technology should be compared to the 0,23 – 0,37 M€/MW that Risø expect by 2020. A price reduction of 10 to 13 % has to be obtained on an annually basis in order to reach the Risø target. Significantly larger hydrogen plants (one - two orders of magnitude larger), economics of scale, automation, production in low cost countries and a technological shift from alkaline electrolysers to SOEC are the main factors to drive down the cost.

It is assumed that it is technically possible to utilize 90 per cent of the excess heat for district heating. At any point on a district heating "cold flow" pipeline a heat exchanger can be added which is coupled to an electrolyser. The principle is shown in the figure below. In the future it might be economical feasible to utilize heat from SOEC on the "hot flow". Future possible heat utilization is indicated by the dotted line in the figure below.

Figure 6 – Utilization of heat from an electrolyser



C.1.2 Future high temperature solid oxide electrolyser cells

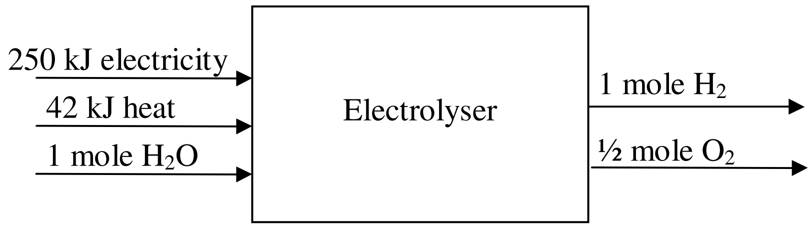
High temperature electrolyses are not yet developed. In this technology sheet an estimate of the technology data for such future technology is presented. All values presented on the efficiency of the cells are based on the lower heating value (LHV).

The data presented here represents an update and expansion of the data sheet used by the Danish Energy Authority from (DEA) March 2005.[47] The updates are mainly based on input from Professor Mogens Bjerg Mogensen and Scientist Søren Højgaard Jensen from the Fuel cells and Solid State Chemistry Department at Risø National Laboratory for Sustainable Energy – Technical University of Denmark.

Two sets of data are presented for high temperature solid oxide electrolyser cells (SOEC). One which represents the theoretical maximum efficiency with ideal conditions and one with electrolysers where 10 per cent heat losses are included, as a proxy for including balance of plant consumption and losses. The data are presented for hydrogen and CO_2 electrolysers. For use in energy system analyses the second set of data which includes these losses are recommended. The technology is still in the early development stage. It is anticipated that commercial electrolyser plants will be available from 2020. It should be noted that such technology and cost data are connected to considerable uncertainties.

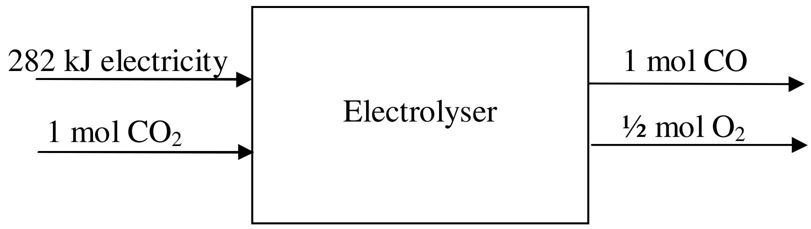
Theoretical maximum for high temperature electrolysers
Energy balance based on ideal theoretical conditions for SOEC is based on the production of 1 mole of hydrogen and illustrated in Figure 7. 1 mole of hydrogen represents 242 kJ.

Figure 7 – Theoretical optimal operation conditions in high temperature hydrogen electrolyses



The inlet heat is used by evaporating water. The inlet heat should be delivered at ~250°C at ~40 atm. Considering that the heat is "free" the electricity to fuel efficiency is 96.8 per cent. Considering that the heat is not "free" the electricity and heat to fuel efficiency is 82.9 per cent with ideal operation conditions (assuming that the heat origins from electricity). For CO_2 electrolyses the same ideal theoretical conditions are illustrated in Figure 8.

Figure 8 – Theoretical optimal operation conditions of high temperature CO_2 electrolyses



The electricity to fuel efficiency is 99.3 per cent with ideal operation conditions in the case of CO_2 electrolysis. In this case totally pure CO_2 has to be delivered.

Future possible high temperature electrolysers
High temperature electrolyses cannot be expected to operate with ideal operation conditions. For energy system analyses it is recommended that the following data are used, in which 10 per cent heat losses have been included. Such low value heat however can be used in district heating systems, where other fuel can be replaced. The 10 per cent heat losses are losses to the surroundings. For larger units the losses may be smaller. Another possibility in the future is that the losses are lower than the 10 per cent, because the heat can be utilized for preheating water.

In

Figure 9 the operation conditions for high temperature hydrogen SOEC is presented. Considering that the heat is "free" the electricity to fuel efficiency is 88.0 per cent and the electricity to low value heat efficiency is 9.1 per cent. Considering that the heat is not "free" the electricity and heat to fuel efficiency is 76.3 per cent and the electricity and heat to low value heat efficiency is 7.9 per cent.

Figure 9 – Potential future operation conditions of high temperature hydrogen electrolyses

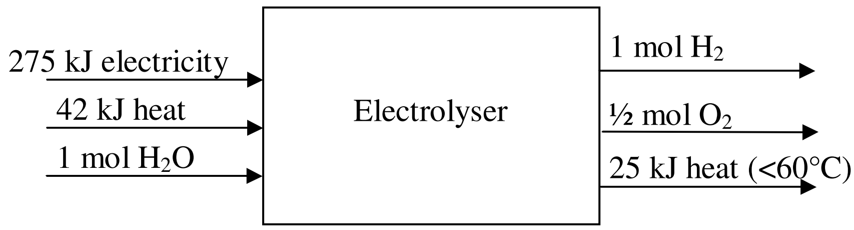
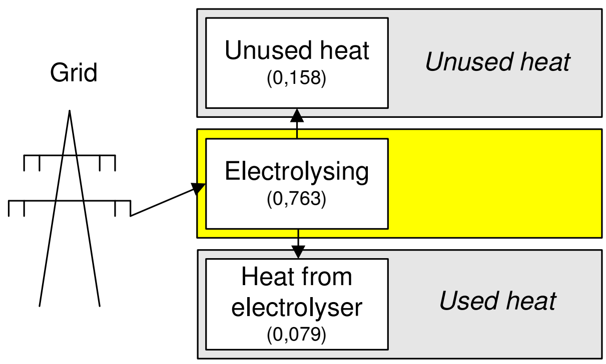


Figure 10 – Potential future operation efficiencies of SOEC with heat utilization

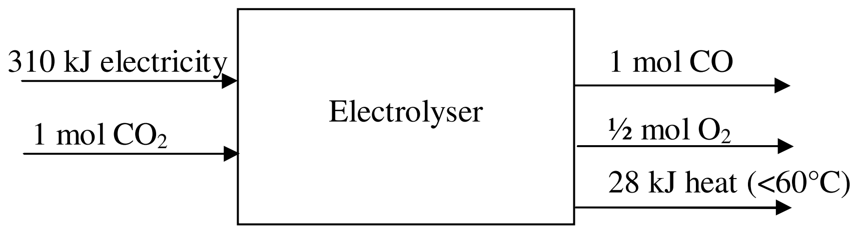


As stated earlier energy can neither emerge nor disappear. As stated above 76,3 per cent of the electricity is assumed converted to hydrogen and 7,9 per cent of the energy is assumed converted to useful heat. That means that 15,8 % of the energy is unused heat and thereby waste as illustrated in the figure to the left.

High temperature CO_2 electrolyses is presented in later figure. In this case it is recommended to use 90.3 per cent electricity in fuel out efficiency and 9.0 per cent electricity in low value heat out efficiency. Losses due to the purification process of CO_2 has to be added.

High temperature CO_2 electrolyses is presented in Figure 11. In this case it is recommended to use 90.3 per cent electricity in fuel out efficiency and 9.0 per cent electricity in low value heat out efficiency. Losses due to the purification process in the procurement phase of CO_2 have to be added.

Figure 11 – Potential future operation conditions of high temperature CO_2 electrolyses



The H_2O and CO_2 electrolyses can be combined and the electricity and heat consumption can be calculated linearly by combining the operation parameters presented above. This has been tested at Risø National Laboratory at 850 °C and the cell performance seems to change quite linear from pure H_2O/H_2-performance over mixed H_2O/H_2- CO_2/CO-performance to pure CO_2/CO-performance.

The cells have fast regulation abilities (from 0% to 100% power in less than a few seconds) if the cell temperature is kept at the maximum operating temperature. If the cell is operated below 100 % power a heat supply is needed to keep the cell temperature at the maximum operation temperature. The heat-supply-device can be fairly simple and is not considered a significant cost component. Operation below 100% power (or below thermo-neutral-potential (E_{tn} = 1.3 V) does not affect the electricity-to-fuel-efficiency. That is because the heat supply equals the reduction of the electricity consumption in the cell (i.e. the total voltage (cell + heat supplier) is 1.3 V regardless of the power ratio). The start-up time of SOEC is a challenge, however different operation and insulation strategies can be applied in the SOEC-plant in order to keep the plant at operation temperature. If the SOEC is cold the start-up time is several hours.

When using the electricity to fuel efficiencies the DC/AC inverters also has to be considered as well as the potential losses in the fuel storages. For the inverters 5 per cent losses should be added.

The costs of future high temperature electrolysers
According to DEA[48] the costs of solid oxide electrolysers is 0.18 M€/MWe, with a lifetime of 20 years. However there are extra costs of connection electrolysers to the grid, because normally the grid is designed to move electricity to larger transmission lines. The costs are estimated to be 66,000 66,000 €/MW grid connection. The lifetime is assumed to be 30 years for the grid connection. The total investment costs of grid connected electrolysers is thus 0.25 M€/MW.[49] The fixed operation and maintenance (O&M) costs are 5,400 €/MW/year which is approx. 3 per cent of the initial investment annually.[50] The replacement of cells in the lifetime of these electrolysers is included in the fixed O&M costs. With such assumptions the total annual costs are 0.021 M€/MW using a socio-economic interest rate of 3 per cent.

At Risø National Laboratory for Sustainable Energy a total investment of between 0.23 and 0.37 M€/MW is expected. Here one third of the investment is the electrolyser cells, which has a lifetime of 10 years. The rest is assumed to be the BoP equipment/plant and has a lifetime of 30 years. Here the fixed O&M cost are estimated to be 0.5 per cent of the initial investment. Including grid connections the total annual cost are between 0.021 and 0.031 M€/MW.

In the cost estimates recommended, the total plant including grid connection is based on the estimate from the DEA and on the low estimate from Risø. The investment cost are assumed to be 0.25 M€/MW for grid connected electrolysers with a 20 year lifetime and 2 per cent fixed O&M costs. These cost estimates are based on future large-scale production of electrolysers and is an estimate for the socio-economic costs from between 2020 – 2030.

Table 6 – Potential operation conditions of high temperature- and current alkali electrolysers

Technology		**High temperature electrolysers (SOEC)**		**Alkali electrolysers**
Production of		Hydrogen	CO	Hydrogen
Year available		2020-2030	2020-2030	2008
Capacity	MW	0,5-50	0,5-50	0.9-2.0
Output	Bar	40	40	1
Operating temp.	°C	850	850	70-90
Electricity to fuel efficiency [4]	% (LHV)	73	86	58-61 [5], [51][52]
Electricity to heat efficiency	% (LHV)	7.5	8.6	30
Other input		Steam[6]	Pure CO_2	Ambient air, water
Start-up time	Hours	0,2[7]	0,2[7]	
Regulation ability				
Fast reserves	MW per 15 min.	Full capacity	Full capacity	Full capacity (in 10 min.)
Regulation speed	% per second	3 down / 0.1 up	3 down / 0.1 up	0.004
Minimum load	% of full load	1	1	20
Economy				
Investment costs[8]	M€/MWe	0.25	0.25	0.26-1.4
Fixed O&M costs	% of inv./year	2	2	2.3-3.0
Variable O&M cost[9]	€/MWh	-	-	-

[4] Including 5 per cent losses in inverters
[5] The LHV has been calculated by converting the HHV to the LHV and adding inverter losses. The same LHV occurs if calculated from the cell current density of 1.3 V for SOEC to 1.8 V for alkaline electrolysers combined with inverters. The LHV for commercially available technology is confirmed in the CONCAWE project.
[6] The energy consumption for steam is included in the efficiency.
[7] The start-up time is several hours if started from cold.
[8] Including improvements in grid connection of 66,000 €/MW for large plants.
[9] No variable costs assumed other than electricity.

Lifetime[10]	Years	20	20	20

C.2 Compression

Different storage technologies for hydrogen exists such as pressure, liquefying, hydrides, hydro-carbons, alcohols etc. exist. In this report only pressurized hydrogen is analysed since this is the preferred hydrogen storage method by the top 15 car manufacturers, which produce more than 8/10 of all cars and more than 9/10 of all light commercial vehicles (LCVs) in 2007 (see table below).

Table 7 – OEM's onboard fuel strategies

Company	Compressed H2	Liquid H2	Gasoline and/or methanol reformer	Cars/year	LCV/year
GM	X	X	X	6.259.520	3.055.575
Toyota	X			7.211.474	1.108.333
VW	X	X		5.964.004	256.777
Ford	X		X	3.565.626	2.586.284
Honda	X			3.868.546	43.268
PSA	X			3.024.863	432.522
Nissan	X			2.650.813	641.734
Fiat	X		(x)	1.990.715	536.578
Renault	X		(x)	2.276.044	392.996
Hyundai	X			2.292.075	67.003
Suzuki	X			2.284.139	312.177
Chrysler	X		(x)	754.855	1.779.269
Daimler	X		(x)	1.335.226	257.350
BMW		X		1.541.503	-
Mitsubishi	X			1.100.528	304.273
Top 15 production				46.119.931	11.774.139
World production				56.301.121	12.775.910
Top 15 share of world production				81,9	92,2

Sources:[53][54] X = Current development track. (x) = development track is must likely shut down

Compressing gas requires energy, and the compression work depends on the thermodynamic compression process. The compression work required, and thereby the electricity required, in order to compress hydrogen is primarily a result of the difference between the final and the initial energy states of the gas. A pressure increase from e.g. 1 to 2 bars is an increase of 100 %, whereas an increase from e.g. 200 to 300 bars is an increase of 50 %. Even though the pressure is increased by 100 bar versus 1 bar it takes more energy to compress the hydrogen from 1 to 2 bars than it does to compress the hydrogen from 200 to 300 bars. The smaller the difference between the inlet pressure and the outlet pressure in terms of factors the less energy demanding is the compression, and the more stages the lower is the energy consumption.

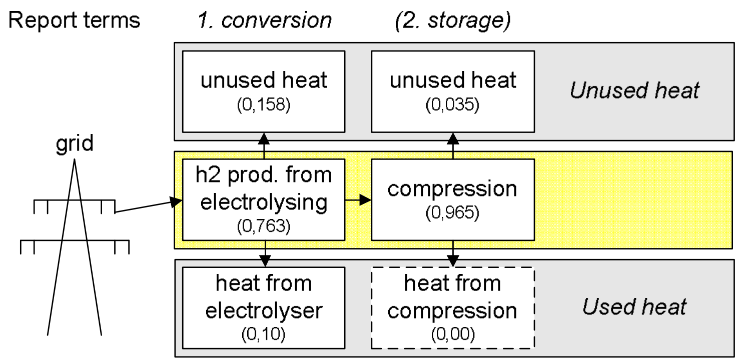
The outlet pressure from the electrolyser / the inlet pressure in the compressor is therefore of great importance. Outlet pressures between 1 and 15 bars are considered to be the most common in the industry at present time.

An inlet pressure of 5 bar is assumed from a current electrolyser. At least 415 / 850 bars is needed in order to deliver 350 / 700 bars to a car.[55] 430 bars outlet pressure are assumed in this analysis. When using a temperature of 15 °C the energy needed to compress the hydrogen from 5 to 430 bars are 4,4 per cent according to the isothermal compression equation and 9,0 per cent according to the

[10] The lifetime for SOEC & the investment and O&M costs includes a replacement of cells and the BoP/plant

adiabatic compression equation. It is confirmed by data from the real compression plants that energy losses at 9,0 per cent are achievable when using medium sized or large compressors with 3 or more compression steps. Therefore a 9 % loss is used for 350 bars vehicles.

Figure 12 – Operation efficiencies of compressors



Increasing the pressure to 850 bars, which is needed in order to deliver 700 bars to a car, increases the energy losses by further 0,9 / 1,0 per cent according to the isothermal and adiabatic equation respectively.

From the figure to the left one can see that see the efficiencies for the two first steps "1. conversion" and "2. storage". Technologies that can decrease the energy used to compress and/or utilize the waste energy will increase the overall energy-chain efficiency.

As described earlier high temperature electrolysers are under development. Using a 40 bar electrolyser outlet pressure results in significantly lower energy-use for compression. Increasing the pressure from 40 to 430 bars requires 2,4 / 3,5 per cent energy according to the isothermal and the adiabatic equations respectively.

3.5 per cent losses is included in the transport scenarios for the compression process of hydrogen to 430 bar from the 40 bar output from high temperature electrolysers. 430 bar is required if the vehicles have storages at 350 bar. The costs of compressors are assumed to be 0.09 M€/MW with a lifetime of 20 years and 2 per cent of initial investment in fixed O&M costs pr. year.

C.3 Storage and distribution of hydrogen

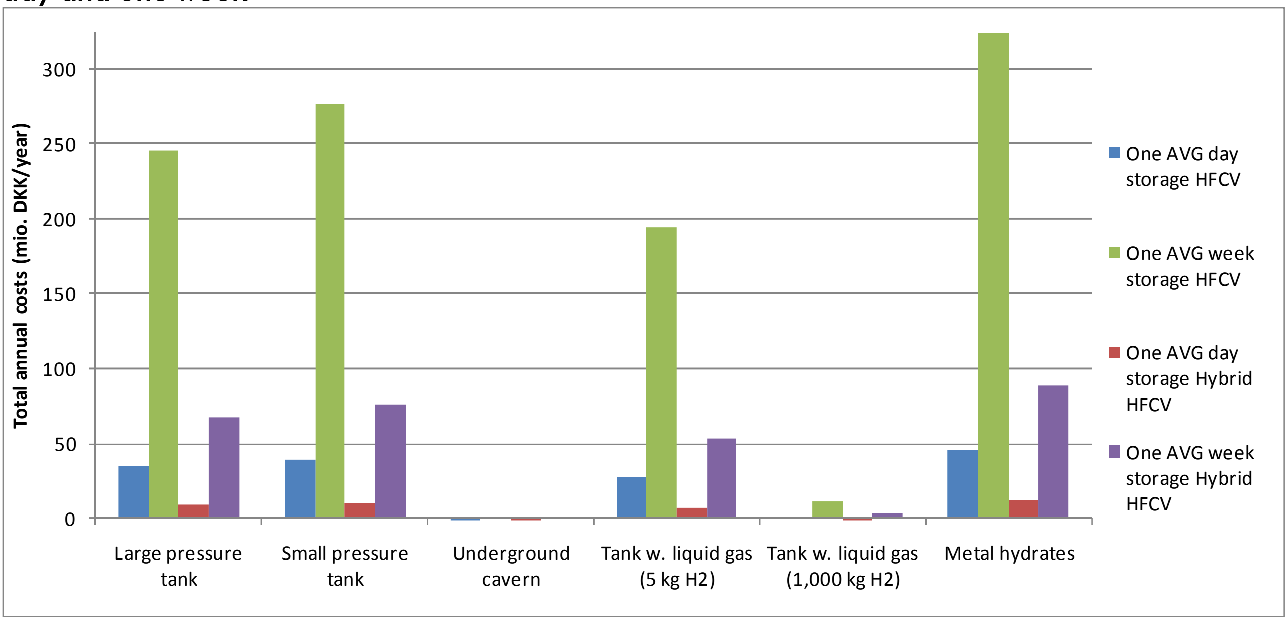
The storage and distribution of hydrogen is a major challenge for large scale production of hydrogen and the roll-out of fuel cells based vehicles.

In a study about hydrogen scenarios for Denmark from 2001, conducted by Bent Sørensen from Roskilde University Center, it was stated that 10 per cent (volume per cent) hydrogen may be possible in the natural gas grid. The Danish grid, which is rather new, is especially suited for this purpose. According to Carsten Rudmose from Naturgas Midt Nord/HNG (Danish gas distribution company) ongoing studies indicate that the European grid may be able to handle up to 20 per cent hydrogen before diffusion and steel hydrogen brittleness becomes a serious issue. Better sealing and other upgrades are however needed. The studies are available from the fall 2009. This is however dependent on the end-consumers as well as the steel type used in the pipeline and the capacity. Some consumers may be able to use a mix of natural gas/biogas and hydrogen. If not membranes have to be installed and/or only parts of the distribution net should be used with a mix of the two gasses.

The Danish Technological Institute is developing membranes, which may separate natural gas and hydrogen at the end user. In future renewable energy systems this may be separation of biogas or refined biogas and hydrogen. For the hydrogen scenarios here the assumption is that the existing natural gas infrastructure can be used for hydrogen in the future. This may pose a problem in the areas where there is no distribution grid; however this can be expanded in the future, if used for hydrogen fuelling stations.

Different types of stationary storage technologies include steel storage tank for gaseous hydrogen or liquid hydrogen in cooled isolated steel tanks or metal hydrates. All of these solutions however are connected to either significantly higher capital costs or lower efficiencies than storage in underground caverns. The cost of hydrogen storage technologies is illustrated in Figure 13 and the volume of different solutions is illustrated in Figure 14 for the HFCV and Hybrid HFCV transport scenarios. The data is based on appendix 2.

Figure 13 – Total annual cost of storage systems for ½ mio. HFCV and Hybrid HFCV vehicles for one day and one week



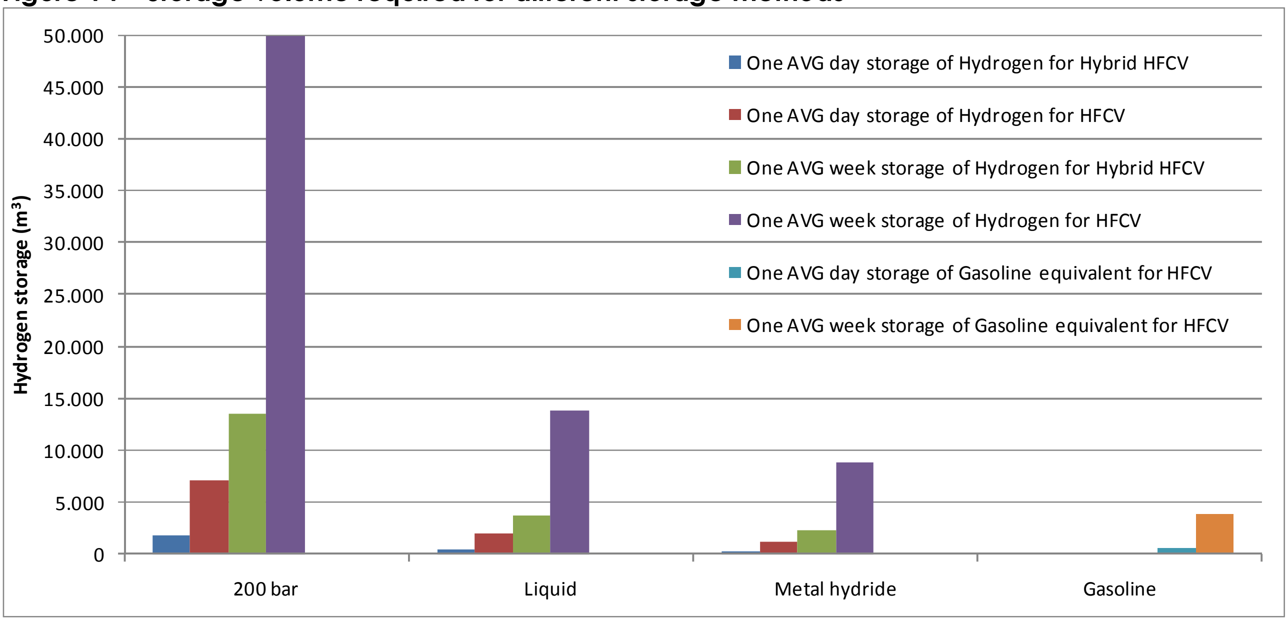
Hydrogen storage in caverns is used in the analyses as this technology is expected to have the lowest costs. The costs of liquid storage is also rather low, however significant amounts of auxiliary power is required reducing the efficiency by app. 30 per cent. The assumption of using caverns is connected to considerable uncertainties and is included in sensitivity analyses.

The Danish natural gas underground storage facilities consist of a TSO (transmission system operator) owned and a privately owned storage. The TSO facility can store up to 710 mio. nm^3 of gas and is divided into 7 caverns. In the analyses here it is assumed possible to use one or more of the smaller caverns for hydrogen, however this would require changes in the caverns and in the operation.[56] The pressure of natural gas in the present caverns is between 160 and 230 bar.

If new pipelines are required the costs of distributing hydrogen in new pipelines are estimated to be twice that of natural gas grids. In the studies here, it is assumed no extra costs are required for the grids, however the costs of caverns are included. The losses in the caverns and in the transmission and distribution are assumed to be 5 per cent here, assuming short storage times. If storage time is increased to one month the losses may be more than 11 per cent in the cavern alone.[57]

In the figure below the storage volume required for different storage methods is seen. Hydrogen storage at atm. pressure is not included. This would increase the volume to between 0.5 and 12 mio. m^3. Gasoline has been included for comparison.

Figure 14 – Storage volume required for different storage methods



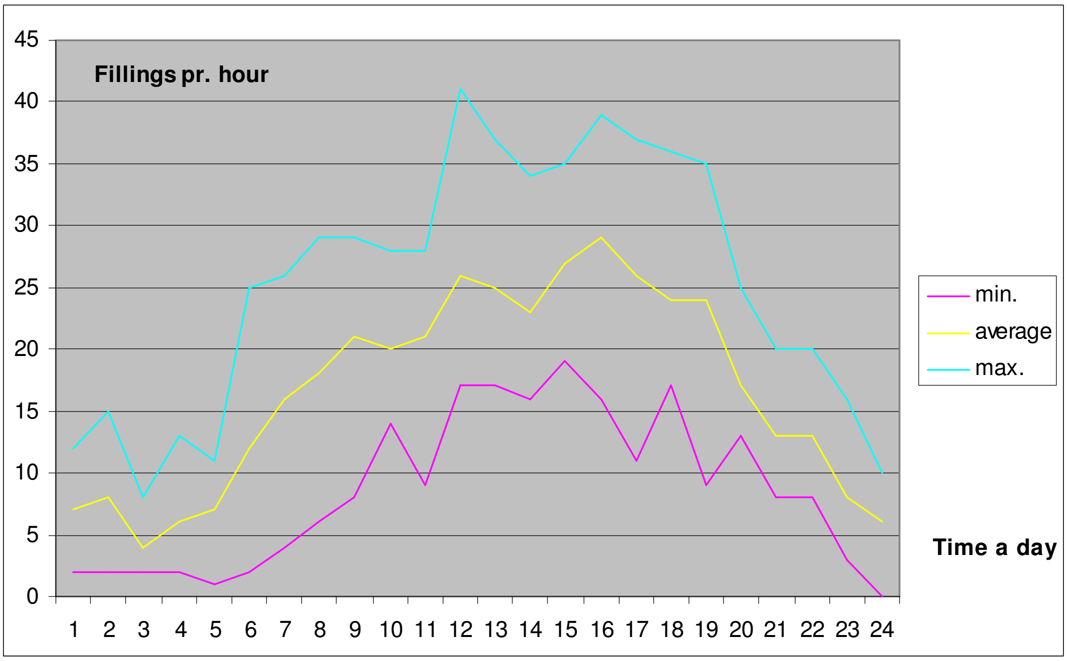
The capacity of the hydrogen storage is one average week. In reality it seems as if marginal higher plant utilization and smaller storages is a more economical solution, however this limits the possibility to use wind power.

C.4 Hydrogen stations

Hydrogen stations are expected to be similar to gasoline station in terms of number vehicle refuelings during a day.

The figure below the number of fillings at typical gasoline station in Amsterdam.[58][59][60]

Figure 15 – Fillings at a typical gasoline station in Germany



A minimum of 207, an average of 384 and a maximum of 615 fillings pr. day where observed.

In the analyses of the ICE vehicles in this report it is assumed that the costs of fuelling station are identical for all scenarios. For BEV no deductions have been made because they do not use fuelling stations. No additional costs are included because of hydrogen fuelling stations. In this respect it should be noted, that hybrid HFCV may require lower amounts of hydrogen fuelling stations than pure HFCV.

For diesel and gasoline the transport infrastructure required is included in the sets of fuel prices used. The refinement of diesel and gasoline is connected to 7 per cent losses from crude oil.[61] These losses are included in the analyses.

D. – TANK-TO-ELECTRICITY AND TANK-TO-WHEELS

In this part stationary units and vehicles are described, first stationary power and secondly hydrogen fuel cell vehicles where emphasis has been put on plug-in hybrid hydrogen fuel cell vehicles.

D.1 Stationary power

In this report only uninterruptible power supply (UPS) and micro combined heat and power (mCHP) is analysed. If a complete analysis of stationary fuel cells where to be conducted large CHP should be analysed as well.

D.1.1 Uninterruptible power supply

An uninterruptible power supply (UPS), also known as a battery back-up provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. An auxiliary power supply or a standby generator does not provide instant protection from a momentary power interruption. A UPS, however, can be used to provide uninterrupted power to equipment, typically for 5-15 minutes until a generator can be turned on or utility power is restored.

A UPS is typically used to protect computers, telecommunication equipment or other electrical equipment where an unexpected power disruption could cause fatalities, serious business disruption or data loss.

The offline/standby UPS offers basic features, providing surge protection and battery backup. The Line-Interactive UPS additionally provides a multi-tap variable-voltage autotransformer. UPS systems are able to tolerate continuous under voltage brownouts and overvoltage surges without consuming the limited reserve battery power. Fuel cell UPS have been developed in recent years using hydrogen and a fuel cell as a power source, potentially providing long run times in a small space. A fuel cell replaces the batteries used in other UPS designs.

A brownout is a short time of low voltage causing lamps to dim or flicker. This is rarely a problem for household appliances but can result in a data processing or communications breakdown.

A power surge is the opposite of a brownout. A short time of high voltage that can be fatal to sensitive IT and other types of equipment.

A UPS fuel cell solution from Dantherm Power works like a Line-Interactive UPS and is a complete power supply/backup solution designed and configured to be installed in both in- and outdoor applications for telecom- and related networks. The solutions can be configured as both integrated and stand-alone modules. The fuel cell technology used is comparable to a stand-alone power generator running on liquid fuel like diesel but it operates in principle like a battery. The Dantherm Power fuel cell solutions thus provide immediate response to power interrupts or total power outage and gives extended back up time of e.g. 24 hours or more. Compared to traditional UPS or diesel generator solutions the comparable fuel cell solutions are characterised by a range of advantages:

- a compact and modular design
- low weight
- ten years life time in normal running conditions
- minimum maintenance
- extended backup time at virtually no extra cost
- no CO_2

no harmful particles or substances
low noise level

The above description of a UPS system – whether based on battery, fuel cell or other technologies – is considered usable throughout the time frame covered in this report. Battery technologies will develop to higher efficiencies, but fuel cells will also evolve to higher and broader levels of operation. Efficiencies and output power are increasing. Furthermore the use of hydrogen as fuel will continue but abilities to also use natural gas and methanol or ethanol as fuels will vastly broaden feasible use cases.

D.1.2 micro Combined Heat and Power

Cogeneration (also known as combined heat and power, CHP) is the use of a power station or a heat engine to simultaneously generate electricity and useful heat.

Conventional power plants emit the heat created as a by-product of electricity generation into the environment through cooling towers, flue gas, or by other means. CHP captures a part of the by-product heat for domestic or industrial heating purposes.

Micro CHP installations usually produce 1-5 kWe in a house or small business. Instead of burning fuel to merely heat space or water, some of the energy is converted to electricity in addition to heat. This electricity can be used within the home or business or, if permitted by the grid management, sold back into the electric power grid.

Micro CHP systems based on fuel cell technology is on the verge of being installed in field trials in Denmark and already in trial in Japan.[62] The first Danish systems will use hydrogen as fuel and shortly after fuel cell systems that can reform natural gas will be in the market.[63]

The Dantherm Power micro CHP is based on PEM fuel cell technology. This enables the system to combine the production of power and heat in one electrochemical process. A fuel cell works by catalysis, separating the component electrons and protons of the reactant fuel (e.g. hydrogen (H)), and forcing the electrons, from the hydrogen atoms, to travel though a circuit, hence converting them to electrical power. The protons travel through a membrane. On the other side a catalytic process combines the electrons with the protons and an oxidant (oxygen (O)) to form the waste product water (H_2O).The heat generated from the catalytic process flows through a heat exchanger, thus storing heat in a water tank. The electrical power is either consumed in the installation or exported to the grid.

By the end of 2008 3,100 - 3,500 fuel cell based mCHP systems will be installed In Japan, which means that Japan is by far the country with the greatest experience in fuel cell based mCHP.[64] In comparison Denmark will expectably have a total about 100 systems installed by the end of 2009. With regards to performance Dantherms fuel cell systems are close to the best Japanese systems.

Table 8 – 1 KW class Fuel cell mCHP system suitable for residential use

Efficiency	PEMFC	SOFC
Electric/Heat (%LHV)	37 / 50	45 / 30
Temperature °C	65-90	700-1000

Source:[65]

Table 9 – 1 KW class Fuel cell mCHP system suitable for residential use

	2008		2030*	
Efficiency	HTPEM	SOFC	HTPEM	SOFC
Electric/Heat (%LHV)	40 / 35-40	24 / 52	62 / 38	65 / 35
Temperature °C	160	750	220	550

Source:[66]

*The electrical efficiency values for 2030 are based on a theoretical maximum with the present technology. However, it is not necessarily the theoretical maximum the manufacturers will strive to reach in the future, but a pragmatic market based trade-off between efficiency and costs. Therefore it is expected that electric efficiencies will grow but advantages in lower size, weight, costs etc. will be valued higher by the market than the absolute maximum of efficiency. This will of course reduce the power generated per stack, but then if someone needs more power they will expectably buy systems with more (cheaper) stacks.

D.1.2.1 Technical assessment – UPS and mCHP

Fuel cell based UPS and microCHP systems presently deliver rather low electrical power in the range of 1-2 KW. Development is expected to show commercially competitive products with capacities of 10-50 times this level within a few years. This is mainly in UPS-installations or grid-balancing systems, where larger capacities are feasible.

UPS-systems are technically designed to be able to react within a split second on power brownouts, surges or complete fall outs. However, to optimise fuel cell life time it would be wise to plan net balancing power activities leaving time to warm up the fuel cell stacks. The catalytic membranes in a fuel cell stack will show less degradation, when protected from cold start-ups.

The possible use of UPS-systems for grid balancing purposes would give a recognisable amount of balancing power. Assessing the owners incitements to set their mission critical power infrastructure at the grid disposal is quite another subject.

If a company wants to protect their equipment from power failures they invest in UPS-systems. If the company should consider letting a grid operator access and use their UPS equipment, it should essentially be risk free for the company – and it should be worthwhile. Practically the UPS system should be able to switch from standby to online grid supply on demand, but any power failure should override grid supply and switch the UPS-system to island mode and supply the local equipment. To secure enough capacity to supply the local equipment with power for the necessary time frame, the UPS-owner would have to store a surplus of fuel than otherwise necessary. A financial model should compensate the company installing the UPS-system for both the variable and fixed costs (depreciation) of the grid use of the UPS-system and the surplus of fuel storage.

This could be done in several ways. For instance the grid company could pay a service fee for having capacity standing by. Furthermore it could pay a certain charge for each KW actually supplied. Another model could pose a different angle. The grid company owns the UPS and leases this as a service with a specified service level to the company. Maybe this model would leave the UPS-system to be in operation to a further degree and show a more efficient investment profile.

The supply of power to the grid (upload) is limited to the output power level of the UPS or mCHP. The present Dantherm models can deliver 1.6 KW/-48V DC and 1 KW/-48V DC respectively. This for as long as there is hydrogen available. In a UPS-installation the hydrogen is usually bottled and limited to a guaranteed 24 hours of operation. It is, however, not unlikely that bottle capacity could be doubled in some installations. In a mCHP installation hydrogen would probably be supplied much like natural gas is distributed.

Already in 2009 UPS systems with capacities of 5, 10, and 15 KW are available in a modular design. Therefore all relevant UPS needs up to 100 KW effect can effectively be satisfied.

For grid balancing purposes there should obviously be a download/storage scenario of excess power. In this matter a battery can be considered a single infrastructure for both upload and download. This is not the case with fuel cell systems. In order to store excess power, the electricity could be used to generate hydrogen in an electrolytic process. Thereby the hydrogen, which is storable, could carry the energy until the hydrogen is used in the fuel cells. The download/storage scenario is described elsewhere in this report.

As an analogy to the operational and financial scenarios of using the UPS-systems for grid balancing, the households and thereby the micro CHP should have the possibility to override the request for grid upload, if a local need is not covered. An economic relevant compensation would be necessary to motivate the availability to draw on the mCHP. The economic compensation paid by the system entity (Energinet.dk) will necessarily be lower when the owner of either a UPS or a micro CHP can overrule the decision to deliver and/or receive power and energy to/from the grid compared to the case, as of today, where the system entity has full control over the up/down regulation device. What influence, this has on the economic compensation that the system entity is able to pay for the up/down regulating ability, has to be further investigated.

D.1.2.2 Fuel cells and electrolysers for heat and power

Stationary fuel cells in combination with electrolysers can be implemented in areas outside district heating areas, where oil, natural gas or wood pellet boilers can be replaced with biogas or hydrogen micro fuel cell (mCHP) in individual households. Stationary fuel cells can also be implemented within district heating areas in combination with electrolysers. In such a situation they can replace single or combined cycle gas turbines and can be operated on syngas, biogas, natural gas or as is the subject of the analyses hydrogen.

The aim of the analyses is not to evaluate the feasibility of district heating in comparison with individual heating systems. Such analyses have been conducted recently elsewhere, where it was concluded that it is feasible to expend the Danish district heating areas from 46 per cent of the net heat demand to between 53 and 70 per cent.[67]

The alternatives analysed are constructed so that each electrolyser option is compared to a number of relevant alternatives for integrating intermittent resources. The following electrolyser options are analysed:

- Electrolysers for individual household micro fuel cell CHP (hydrogen micro FC CHP)
- Electrolysers for small distributed or large-scale central combined heat and power plants, which are connected to district heating grids (hydrogen CHP).
- Large fuel cells for replacing gas turbines and gas engines and
- Fuel cells in UPS

When evaluating the appropriateness of using such technologies for balancing renewable energy, a reference has to be established. The reference technologies used are natural gas boilers for the individual technologies.

D.2 Reference Car

In order to have as high a transparency between different car setups a reference car is defined. This car is the same as the one used by DEA[6869] and is defined as a;

- medium sized car the same size of e.g. a Toyota Corolla 1,6 l gasoline
- 74 KW engine
- Curb-, average driving- and gross vehicle weight of 1.200, 1.325 and 1.850 kg respectively
- 18.000 km/yr
- Average energy use of 0,36 MJ/km
- Price of 77.000 DKK excl. taxes and VAT
- Average lifetime of 13 years.

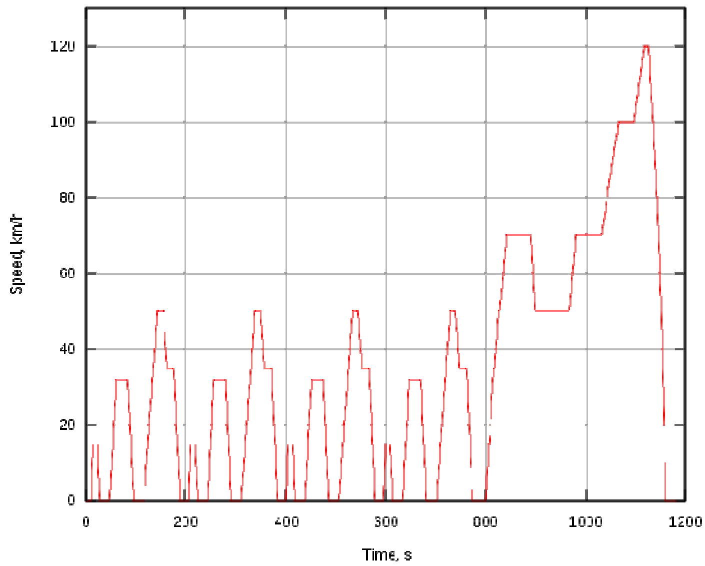
The difference between the curb and average driving weight of 125 kg consists of a 68 kg driver, 7 kg luggage and 50 kg fuel, coolant, oils, tools and spare wheel.[70]

In further analysis values for Cw, frontal area, rolling resistance and auxiliary power should be included as well since these datas largely influence the energy consumption pr. km under different drivecycles. It is recommended that future Danish analyses are based on the dataset provided by European Commission Joint Research centre, since this dataset is believed to be coherent easy to use and is updated on a regular basis.[71]

D.2.1 Driving cycles

Cars should optimally be tested according to the same standards. Only by doing so it is possible to e.g. evaluate which car is the most fuel efficient. In Europe the New European Drive Cycle (NEDC) is the by far the most widely used drive cycle. The NEDC is a driving cycle consisting of four repeated ECE-15 driving cycles and an Extra-Urban driving cycle, or *EUDC*.[72] The NEDC is supposed to represent the typical usage of a car in Europe, and is used, among other things, to assess the emission levels of car engines. In the figure below the four ECE-15, the one EUDC on the combination – the NEDC is seen.

Figure 16 – The New European Driving Cycle



The average speed of the NEDC is 33,6 km/hr and the test is 1.180 seconds.[1173] Some electric cars have a maximum speed which is lower than the topspeed of 120 km/hr that is required in the NEDC. Therefore some European electric cars, are not tested according to NEDC. Furthermore many Japanese and American electric cars are tested according to Japanese and American drive cycles respectively. This makes it difficult to compare different electric cars against each other.

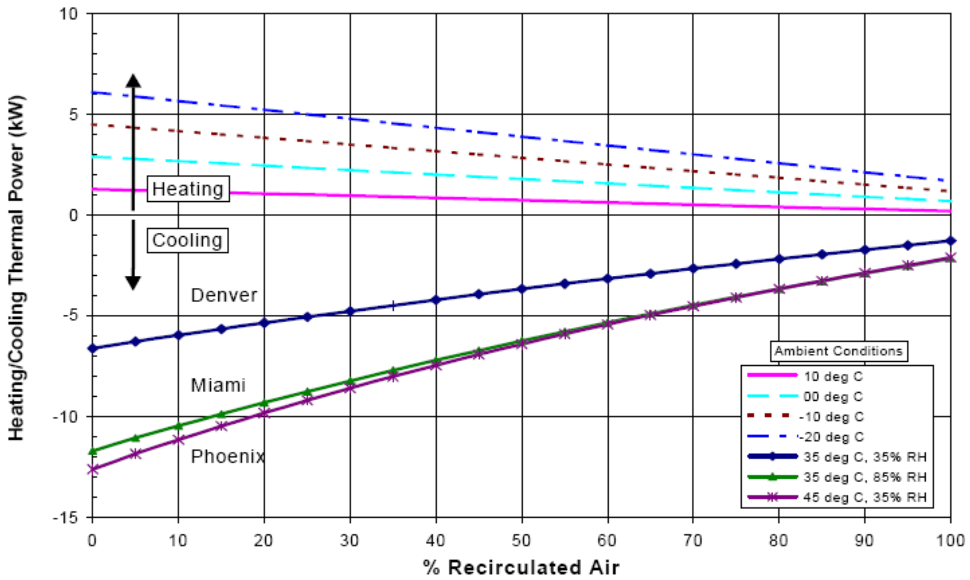
[11] ((18,7 km/hr * 780 sec.) + (62,6 km/hr * 400 sec.)) / (780 + 400) = 33,6 km/hr.

D.2.2 Energy consumption for cabin heating and cooling

Energy for cabin heating and cooling in electric vehicles needs to be taken into account when considering the electricity draw from power grid to electric vehicles. The energy consumption for cabin heating and cooling in vehicles depends to a wide extent on the ambient air temperature and humidity at the location where the vehicle is used and the rate at which the air inside the cabin is re-circulated. Few studies have been published on the energy consumption for heating/cooling in relation to ambient temperature/humidity and air recirculation rate. Most of these studies date back to the late nineties and with emphasis on USA climate conditions due to the general focus on battery vehicles in especially California at that time.

The figure below show the results of a 1999 study from NREL on potential energy consumption from heating and cooling as a function of ambient temperature/humidity and air recirculation rate in the cabin.

Figure 17 – Heating & cooling thermal power requirements



Source: [74]

When cooling the vehicle cabin the ambient relatively air humidity (RH) is a factor that can more than double the cooling load. This can be seen by comparing the cooling load in Denver to that in Miami as shown in the figure. Where the ambient temperature and humidity is given by the location the recirculation rate of air can be controlled in the vehicle. The less outside air brought in for ventilation the less thermal requirement for cooling/heating, however increased recirculation of air poses two challenges concerning:

1) removing odors, bioaerosols, and harmful volatile organic compounds
2) Controlling humidity levels to avoid condensation on cold surfaces in either the heating mode (such as cold windows) or the cooling mode (such as cooled seats, pipes, or ducts).

According to the NREL study up 70 % air recirculation during heating and up 80 % during cooling may be acceptable whilst still securing an acceptable change of air in a vehicle with for four passengers. Given this assumption the following thermal power requirements can be drawn from the previous figure:

Table 10 – Thermal energy requirement for vehicle cabin heating & cooling

Ambient temperature	Thermal energy requirement	
	Heating @ 70 % air recirculation	Cooling @ 80 % air recirculation
- 20 °C	~ 3 KW	
- 10 °C	~ 2,2 KW	
0 °C	~ 1,3 KW	
+10 °C	~ 0,5 KW	
+ 35 °C @ 35% relatively air humidity		~ 2,2 KW
+ 35 °C @ 85% relatively air humidity		~ 3,7 KW
+ 45 °C @ 35% relatively air humidity		~ 3,7 KW

When using a vehicle year round energy consumption for cabin cooling and heating will vary a lot depending on the local climate conditions at the day of use. An American study from 2000[75] suggests that use of air conditioning in a vehicle used in the USA are turned on 43 % - 49 % of the time the vehicle is in use.

It has not been possible to find any studies that predict energy consumption for cabin heating/cooling in a vehicle used in European or Nordic climate conditions. Based on average temperatures in Denmark and simple assumptions based on the previous findings a simplified attempt to estimate the energy consumption for cabin heating/cooling in Denmark is suggested below.

Monthly average day and night temperatures in Denmark from 1961 to 1990 are used from Danish Meteorological Institute.[76] It is assumed that cabin heating is applied when the ambient temperature is below 10 degrees Celsius and air conditioning is applied when temperature exceeds 20 degrees Celsius. For cabin cooling a relatively air humidity level on average 85 % is assumed.

Based on the above assumptions a simplified monthly use of cabin cooling/heating has been suggested in the table below.

Table 11 – Theoretical need for cabin temperature regulation in Denmark

Temperature *Celsius Degrees*	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Day temp.	2,0	2,2	4,9	9,6	15,0	18,7	19,8	20,0	16,4	12,1	7,0	3,7
Average temp.	0,0	0,0	2,1	5,7	10,8	14,3	15,6	15,7	12,7	9,1	4,7	1,6
Night temp.	-2,9	-2,8	-0,8	2,1	6,5	9,9	11,5	11,3	9,1	6,1	2,3	-0,7
	Heating may be required			Cooling may be required				Temperature regulation may not be required				

As can be seen from the table no average day temperature exceeds 20 degrees Celsius thus theoretically no air condition is needed in Denmark. However some days each year there are temperatures above 20 degrees Celsius in Denmark and even at lower temperatures solar heating of cabin may result in a much higher temperature inside the vehicle compared to the ambient temperature thus requiring air conditioning. It is therefore assumed that air conditioning in June, July and August during day is needed. Overall this means that in 7 months heating is needed and in 3 month cooling is needed, while no cabin temperature regulation is needed for 2 months. Note that this is a simplified model. Real data's are needed in order to determine the actual needs.

Securing energy for cabin heating and cooling in electric vehicles
In conventional ICE powered vehicles heating of cabin does not affect the vehicle energy consumption or operation range as excess heat from the engine cooling systems is utilised for cabin heating. Air conditioning however results in increased energy consumption thus affecting operation range. However as fossil fuels can be refuelled at refuelling stations in few minutes the increased consumption and lower operation range causes no real impact on consumer convenience in use of the vehicle.

In fuel cell electric vehicles excess heat from the system may also be used for cabin heating without significantly affecting energy consumption or operation range. As fuel cell electric vehicles have the potential to offer similar operation range and fast refuelling as ICE powered vehicles the increased energy consumption and lower operation range from air conditioning causes no real impact on consumer convenience in use of the vehicle. However when estimating the possible electrical draw from the power grid in producing hydrogen for fuel cell vehicles the higher energy consumption for kilometres driven with air conditioning should be taken into account.

In battery electric vehicles no useable excess heat is available due to the very high energy efficiency and heat have to be secured either through electrical heating or by use of an onboard fossil fuel burner. Using electricity for heating will increase the vehicle energy consumption and reduce operation range of the battery electric vehicle significantly. The same accounts when using energy for air conditioning. As operation range of a battery electric vehicle in general are significantly lower than ICE and fuel cell powered vehicles and refuelling time may take longer, increased energy consumption due to heating and cooling will have a higher impact on operation range.

A NREL study on use of electricity for air conditioning in a battery electric vehicle in USA shows that operation range may be reduced with between 7% to 16% when air condition load is increased from 0,5 kW to 1,5 kW and 18% to 38% when increased from 0,5 kW to 3,5 kW.[77] According to the study an air condition load on 1 kW at steady-state air-conditioning may meet the air conditioning requirements for a small sedan vehicle. No other studies have been found on the impact on operation range of battery electric vehicles when using electricity for either cabin heating or cooling.

Below impact of operation range for a TH!NK City battery electric vehicle operated at various conditions have been gathered from the vehicle manufacturer Think Technology ASA.

Table 12 – TH!NK City battery electric vehicle data

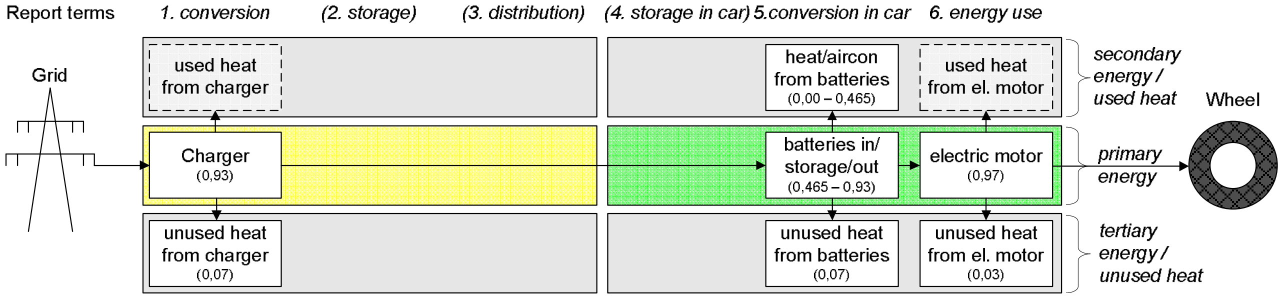
Parameter[1]	**Data**
Electrical heater *max load (KW)*	4
Air Conditioning *max load (KW)*	~4
Range IEC *summer tires, heater off (km)*	170
Range FUDS *summer tires, heater off (km)f*	180
Range EU UDC (km)	203
Range FUDS winter[2] *winter tires, constant 4 kW heater (km)*	90

1: All data stated by Think Technology ASA based on MES DEA – Zebra, 28.3kWh sodium battery. 2: Typical range in parti-cularly cold conditions. Data from previous version of www.think.no. Data no longer available on website. Sources: [78][79]

As can be seen from the data the load of the electrical heater and air conditioning in the TH!NK city battery electrical vehicle correspond well to the findings in the previous mentioned NREL studies. Further the data show that the operation range of the vehicle is reduced by 50 % when heater is turned on and vehicle is used in particular cold conditions.

In the figure below the battery energy-chain is seen assuming 93 per cent efficient chargers, 93 per cent efficient batteries and 97 per cent efficient motors. Furthermore the energy consumption for heating/aircon compared to driving is based on the energy needs in a Th!nk when drived in FUDS drive cycle.

Figure 18 – Battery-energy-chain for battery electric vehicle



Better insulated cars as well as more advanced heating and cooling technologies such as heat pumps will most likely reduce the energy need in future electric cars. Insulation adds weight and there are therefore limits to how much insulation one can add without jeopardising the energy consumption pr. km driven. Since the front window has to be ice-free it is difficult (but not impossible) to use double glazed windows in cars.

The efficiency of air to air heat pumps is largely depending on the temperature difference between the inlet and the outlet air, that is the temperature outside the vehicle and the temperature needed inside the vehicle. The bigger the difference the lower is the Coefficient of Performance (COP). It is assumed that the COP is 2,3 at -10°C, 2,6 at 0 °C and 2,8 at 10 C°.[80] Assuming 0 °C and 70 % recirculation of air the energy use will be 0,5 KWh/h. If the BEV200 is used in NEDC (at 33,6 km/hr) and at an energy consumption of 110 Wh/km, then the energy use pr. hr increases from 3.696 Wh/h to 4.196 Wh/hr. The energy consumption pr. km is thereby increased from the earlier stated 110 Wh/h to 125 Wh/km. Under these conditions the erngy use pr. km is increased by 14 % compared to the case where the heater is of. At 125 Wh/km the distance one can drive in the BEV200 is reduced from 200 km to somewhere between 175 and 180 km.

For BEV heaters and/or air-condition will always require a substantial amount of electric energy and thereby reduce the actual distance that a BEV is able to cover on a fully charged battery. In the future electric cars should be tested in drive cycles that take into consideration the heater.

Further investigations into this subject are needed in order to give an estimate of the combined electricity and heat efficiency as well as the influence on km driven in a BEV. Here a rather pessimistic estimate for heating systems in BEVs are considered in sensitivity analyses.

D.2.3 Life expectancy of gasoline and diesel cars

In order to know whether it is worth to use the battery and/or fuel cell system to hybridize the electricity grid one needs to know the life-expectancy of the battery, the fuel cell system and the car itself. Normally the driveline (ICE's in most cars) and the car itself have similar life-expectancies. They are in other words aligned. If e.g. the ICE had an expected lifetime higher than the car itself the ICE would be designed to well. If the battery and/or the fuel cell systems are to be used for grid balancing there has to be free lifetime in these. Otherwise hybridization of the electricity grid, the operator has to pay an additional price for the tear of the batteries and/or fuel cell system.

In the table below the average lifetime for gasoline and diesel cars in Europe are listed.

Table 13 – Average lifetime for cars in Europe according to Concawe

	Gasoline	Diesel
Vehicle lifetime (years)	13	15
Km/year (km)	13.517	17.972
Km/vehicle calculated (km)	175.721	269.580
Km/vehicle Concawe (km)	175.000	275.000

Source: [81]

It is seen that a gasoline car have an average lifetime of 13 years and 175.000 km and that a diesel car has an average lifetime of 15 years and 275.000 km.

One thing is the average numbers. Another thing is the design life. It is assumed that the automakers in general design their cars to live 50 per cent longer than the average and to drive 30 per cent longer pr. year than the average number indicates. This is equal to a doubling of the km/vehicle to 350.000 km for gasoline and 550.000 km for diesel cars (see the table below).

Table 14 – Assumed design-life of cars in Europe

	Gasoline	Diesel
Vehicle lifetime (years)	13 * 1,5 (19,5)	15 * 1,5 (22,5)
Km/year (km)	13.517 * 1,333 (18.018)	17.972 * 1,333 (23.957)
Km/vehicle calculated (km)	351.354	539.025
Km/vehicle assumed (km)	350.000	550.000

The Danish car market is, due to very high taxes and VAT, a very special market. The average car gets significantly older and drives significantly longer than the average car in Europe. In 2006 the vehicle lifetime was 17 years and the average mileage driven when scrapped was more than 335.000 km (see table below).

Table 15 – Average lifetime for cars in Denmark

	Average
Vehicle lifetime (years)	17
Km/year (km)	19.729
Km/vehicle estimated (km)	335.393

19.729 km/yr is equal to 54,05 km/day in average. In the table below the percentages of the Danish car fleet pr. 1st of January 2006 which was more than X years old. It is seen that 5,9 and 4,6 of the Danish cars was older than 19 and 20 years respectively.

Table 16 – Share of Danish car fleet (2006) being more than 19 years old

Years	% of car fleet
19	5,9
20	4,6
21	3,8
22	3,4
23	3,1
24	3,0
24+	1,5

It is assumed that most automakers design their cars for the 95% quantile, and that this fractil is at 19,5 years and/or 350.000 km for a gasoline car. In 2006 89% of the Danish car fleet was gasoline cars and only 11 % diesel cars.[82] It therefore seems as if the assumptions are reasonably precise. Variations between different brands will occur.

It is assumed that the speed of a gasoline and diesel car is 33,6 km/hr as in NEDC. According to these assumptions a gasoline and a diesel car has a design life of 10.000 and 16.000 hrs respectively.[83]

D.2.4 Transport demand and distances travelled

The Danish Transport Research Institute at DTU Transport performs National Travel Surveys for passenger transport. The data is gathered through telephone interviews and recently via the internet. The earliest data is from 1975 the latest from 2006 and the data is available online. Here selected datasets from 2006 is used which is based on app. 2.000 persons transport habits.

The dataset in the National Travel Surveys contains detailed information about modes of transport, length of trips, transport times, purpose of trips, age, income, residence etc.. In this context the most important data is on the length of trips in road transport, however data on other modes of transport is also available. Here the data from 2006 is presented.[84]

All transport demands in Denmark has been listed. The category "driving car" the transport demand from trips below 50 km represents more than 60 per cent of the km travelled. Approx. 95 per cent is represented in trips below 150 km.

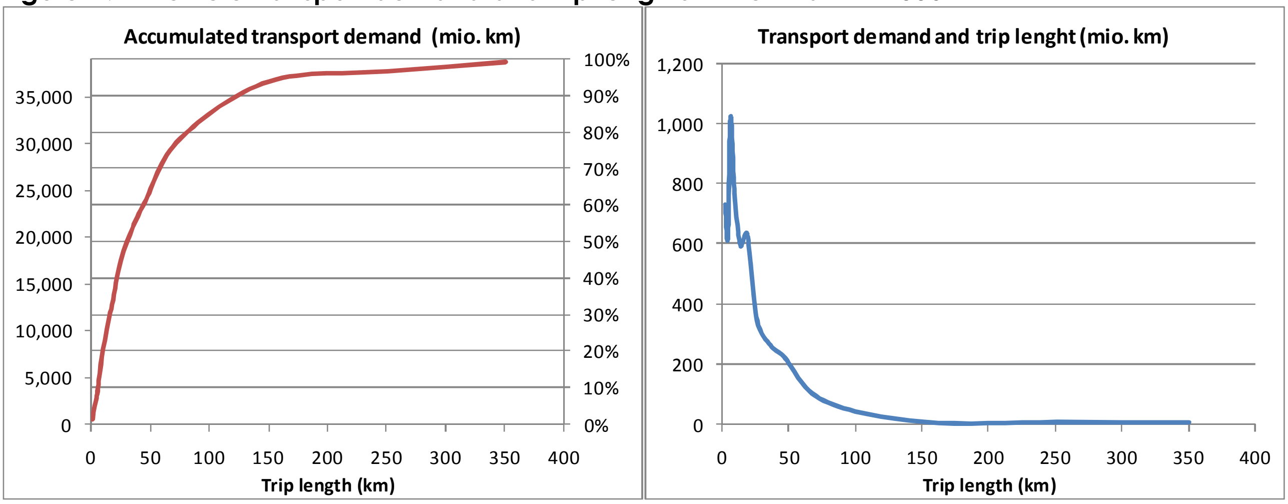
Table 17 - Length of trips and modes of transport in mio. km for Denmark in 2006

Length of trip Mio. km	Other	Walk	Bicycle	EU-moped / motorbikes	Driving car	Van / truck	Passenger in car	Bus	S-Train, metro	Train	Sum
1-2 km	4	612	528	18	618	18	93	34	4		1.929
3-4 km	7	233	519	33	1.466	78	288	87	17		2.728
5-6 km	20	110	404	39	1.250	73	340	145	32	5	2.418
7-10 km	38	32	378	91	3.076	170	780	295	71	14	4.945
11-15 km	59	12	210	87	3.472	166	969	303	151	47	5.476
16-20 km	60	3	82	66	2.981	272	891	178	177	131	4.841
21-30 km	50	5	68	69	4.767	367	1.304	208	380	170	7.388
31-40 km	47	6	31	35	3.479	252	802	147	309	305	5.413
41-50 km	18		64	20	2.652	332	839	16	84	291	4.316
51-100 km	193		42	33	6.838	968	2.138	100	63	1.040	11.415
101-200 km	293				6.099	740	2.105	119		1.423	10.779
201-300 km	649			49	1.072	416	556	102		883	3.727
301 km -	503				991	775	288	210		906	3.673
Sum	1.941	1.013	2.326	540	38.761	4.627	11.393	1.944	1.288	5.215	69.048
% under 50 km	16	92	98	85	61	37	55	73	74	20	57

Errors in the original data within walking and S-trains has been corrected in collaboration with Carsten Jensen, DTU Transport in Feb. 2008. The category "other" consists of ferry and plane trips among others.

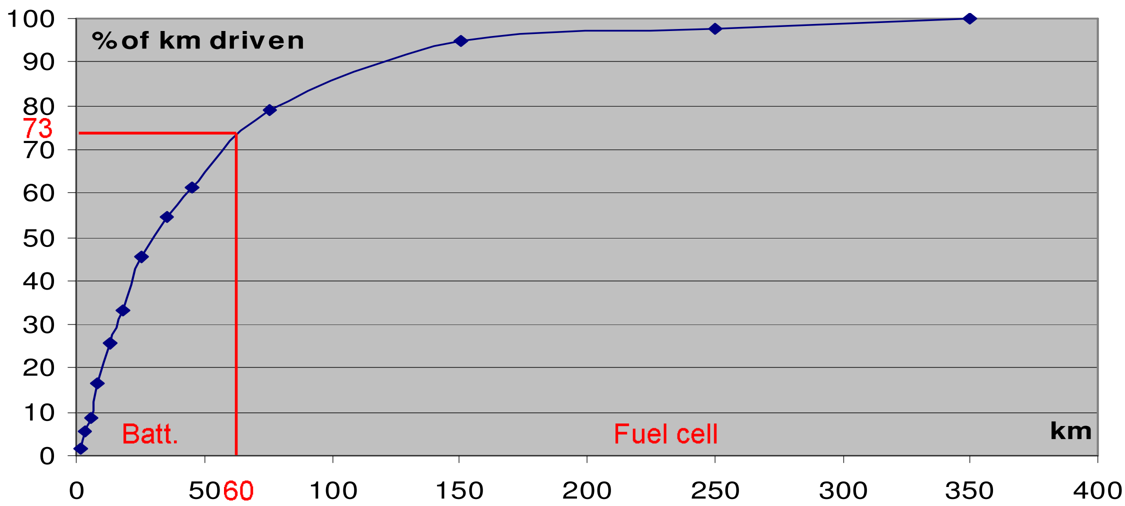
In Figure 19 the category "driving car" is used to illustrate the transport demand in relation to trip length. Such data illustrate that the BEV vehicles used in the analyses here can cover most of the transport demand with ranges of 135 to 200 km.

Figure 19 – Vehicle transport demand and trip lengths in Denmark in 2006



According to data from Department of Transport[85] at Technological University of Denmark most of the km driven in cars in Denmark is driven on relatively short trips. The distribution is seen in the figure below.

Figure 20 – Distribution of km driven in cars in Denmark on a daily basis



A relatively small battery can cover most of the km driven. It is seen that 73% of the km driven on a daily basis are at 60 km or less. A formula for the accumulated transport demand as a function of km driven on a daily basis has been estimated using MathLab. The equation is used to find the distribution between the kilometres driven on batteries and fuel cells respectively.

D.2.5 Availability

When an electric vehicle is not used for driving it can be used to support the grid. It is therefore necessary to estimate how many hrs pr. day the average vehicle is available to support the grid. The average Danish car is according to the DTU findings the transport pattern is 45 km pr. day. The average speed on the Danish roads is considerable higher than the 33,6 km/hr as stated in the NEDC. At 45 km/day and at 45 km/hr the average Danish car is used for 1hr 0 min daily. An average car is therefore maximum at disposal for the electricity grid up to 23 hours a day. The number of vehicles parked is rather high, even in rush hours. Here 20 per cent is used as the maximum number of vehicles parked, which is rather conservative and most likely underestimates the capacity connected. The amount of parked vehicles that are grid connected is assumed to be 70 per cent.

Table 18 – Car usage in Denmark

Average length of trips pr. car	16 km
Average number of trips pr. car pr. day	2,7
Average mileage pr. car pr. day (16 km/trip * 2,7 trips pr. car pr. day)	45 km pr. car pr. day
Average speed	45 km/hr
Average caruseage pr. day (45 km /45 km/hr * 60 min. pr. hr.)	60 min. pr. car pr. day

It is assumed that max. 50 % of the cars are driving at the same time. Share as a function of time. Between 50 and 95 % availability (weekdays mornings vs. nighttime).

Furthermore not all of the energy in the battery can be considered available since people in general demands a certain range buffer that have to be at their disposal at any time a day. The minimal range buffer is required for impulse drives, which can be a trip the nearest 7-11, the nearest hospital (in case of emergency) etc. What the range buffer (d_{rb}) should be is depending on individually needs and requests.

One way to determine the range buffer is to look at what the range buffer is today in different vehicles. Gasoline cars often have reserve tanks holding 5 litres. Assuming 16 km/l this is equal to 80 km. Due to better instrumentation and a higher and more use of GPS, where it is possible to enter "find nearest gasoline station" smaller and smaller reserve tanks are needed. The buffer range in a gasoline car might be much higher than what is needed because of 1) there is space for a large reserve tank, 2) better instrumentation and 3) the possibility to charge the battery almost everywhere. The reserve tank on motorcycles, which have limited space for gasoline tanks e.g. often hold 3 liters or less. Assuming 12 km/l this is equal to a range buffer of 36 km which is significantly less than the average range buffer in gasoline cars.

Finally a US study find that 20 miles (32 km) range is sufficient for most drivers.[86] The 32 km range buffer is used since this number is believed to represent the average need for a range buffer in a future electric vehicle. Since plug-in hybrids can drive on the fuel (whether gasoline or hydrogen) when needed, the range buffer in the battery is defined as zero km ($d_{rbplug\text{-}in\ hybrids} = 0$).

The time dispatched /tdisp) will depend on the electricity market. For spinning reserves typical dispatches are 10 minutes in the US. It is assumed that a typical dispatch in West Denmark is also 10 minutes. This however has to be further investigated. In order to allow for a long repeated dispatch 30 minutes is used. For regulation up and down, power in battery vehicles (e.g. FPBEV and Plug-in hybrids of all kinds) can flow both ways. Regulation dispatches are usually 1 – 4 minutes in the US. The West Danish numbers are unknown, but dispatches of the same length as in the US is expected. This has to be further investigated. In order to allow for the possibility of a long repeated regulation sequence t_{disp} = 20 min. is used.

The fuel cell system in a plug-in hybrid HFCV can only provide regulation up (power from vehicle to grid). Thus, for example, a FCV parked 16 h and providing regulation up only, assuming R_{d-c} of 0,10, would have effective t_{disp} = 1,6 h.

Power capacity of V2G is determined by the lower of the two limits, P_{line} or $P_{vehicle}$. It is shown how this is calculated for each type of vehicle: a BEV, the constructed BEV_{200}, a plug-in hybrid HFCV and a HFCV, the Honda FCX Clarity. The BEV with a range of 200 km has a 21,98 KWh Li-ion battery. It is assumed that this battery can be 100 % discharged without damaging the battery. The vehicle efficiency (η_{veh}) is 9,1 km/KWh (110 Wh/km).

Even though it was found that the average Danish car drives 2,7 trips of an average of 16 km pr. trip it is for simplicity assumed that half the average daily vehicle km would have been depleted when the vehicle is parked and power is requested. In other words d_d = 22,5 km.

D.2.6 Charging and discharging

If assuming 110 Wh/km and a charger efficiency of 93 % one sees the current transfer capacity and the charging time for different kinds of power sockets in the table below. An ordinary power socket (230 V/10 A) can e.g. only transfer 2,3 KW at a time. If one e.g. has a BEV with a range of 200 km using 110 Wh/km, then the charging time for a fully depleted battery is 10 hrs and 17 minutes.[12] If one uses a 230 V/16 A power socket the charging time can be reduced to 6 hrs 26 minutes and if one is using a 3-phased power socket the charging time is further reduced to 2 hrs 9 minutes. It is assumed that most people will not accept a charging time this long. Therefore even bigger current carrying capacities are needed. A 3 –phased high voltage (380 V) 32 A power socket is able to transfer 36,48 KW. The result is a charging time of 39 minutes (0,65 hrs). 39 minutes is however still 13 to 20 times more time compared to gasoline refuelling (assuming a refuelling time at a gasoline station of 2 to 3 minutes). Even if one uses a 3-phased high voltage 64 A one only reduces the charging time to app. 20 minutes. The long charging time is however only a problem when longer ranges are needed. Normally the cars are charged during night time and therefore are not expected to constitute a problem.

The faster the charge the more tear there is on the batteries. Furthermore in general the faster the charge the lower is the energy density. The highest energy density found in the literature on a battery level (not to be confused with "cell" of "module" level) is 117 Wh/kg (@ 7,6 kWh) for high energy and medium power batteries.[87] The 117 Wh/kg is reduced to 93 Wh/kg when high-power medium energy batteries (@ 2,6 KWh) is used. The lower the energy density the heavier is the battery.

Table 19 – Correlation between distance and charging time for different sockets

Distance	Used electricity	Charging electricity	1 230V 10A	1 230V 16A	3 230V 16A	3 380V 16A	3 380V 32A	3 380V 64A
Transfer ca-pacity (KW)	-	-	2,3	3,68	11,04	18,24	36,48	72,96
Km	kWh	kWh	hrs	hrs	Hrs	hrs	hrs	hrs
10	1,1	1,2	0,51	0,32	0,11	0,06	0,03	0,02
20	2,2	2,4	1,03	0,64	0,21	0,13	0,06	0,03
50	5,5	5,9	2,57	1,61	0,54	0,32	0,16	0,08
100	11	11,8	5,14	3,21	1,07	0,65	0,32	0,16
150	16,5	17,7	7,71	4,82	1,61	0,97	0,49	0,24

[12] From 0% SOC to 100% SOC.

200	22	23,7	10,29	6,43	2,14	1,30	0,65	0,32
250	27,5	29,6	12,86	8,04	2,68	1,62	0,81	0,41
300	33	35,5	15,43	9,64	3,21	1,95	0,97	0,49
400	44	47,3	20,57	12,86	4,29	2,59	1,30	0,65
500	55	59,1	25,71	16,07	5,36	3,24	1,62	0,81

Source: [88] Note that a uniform energy consumption of 120 Wh/km at all ranges is assumed. In reality the higher the range the higher the energy consumption pr. km due to higher weight of vehicle.

The more power needed the more difficult it is for the local electricity distributor to distribute electricity. Some of the best high power batteries as of today can be recharged at a rate of 25 times their capacity (C-rate charge). When using a 22 KWh battery this is equal to an electricity draw of 550 KW. Problems associated with controlling a large number of cars drawing 550 KW each will be immense. A C-rate charge of 25 is equal to a charging time of approximately 3 minutes – more or less the same as a refuelling with gasoline takes today. Further analyses and dialog with electricity transmission companies are needed in order to evaluate the maximum permitted power socket for battery electric vehicles.

Finally the larger the transfer capacity the more expensive the chargers are. For both BEV and Hybrid HFCV load station chargers are required. Such units are estimated to costs 5,000 DKK and have a lifetime of 10 years.[89] In the analyses two load stations (one at home and at work) are assumed per vehicle.

Power capacity of grid to vehicles and vehicle to grid
The current carrying capacity of the wires between grid and each single car and between each single car and grid is of the uttermost importance when it comes to balancing the grid. There might be a lot of capacity in the battery or the fuel cell system, but this is of inferior importance if the current carrying capacity is very small.

Three independent factors limit V2G power:[90]

- The current-carrying capacity of the wires and other circuitry connecting the vehicle through the building to the grid
- The stored energy in the vehicle, divided by the time it is used
- The rated maximum power of the vehicle's power electronics.

If there are energy left in either the batteries or in the hydrogen tank the lowest of these three limits is the maximum power capability of the V2G configuration. Vehicle-internal circuits for electric vehicles are typically upwards of 30 kW. On the vehicle side the first automotive power electronics unit designed for V2G and in production in the US provides 240 V 80 A in either direction, thus 19.2 kW at a residence building.[91]

What current-carrying capacity that will be the norm in Europe and in Denmark is not known at current time. If 3-phased 230 V 16 A is assumed to become the norm 11,04 KW can be moved in either direction. Further data collection and analysis are needed on this subject.

In the initial analyses of both the BEV and the Hybrid HFCV they are charged at times when they are grid connected randomly. This is also called dump-charge. They are also analysed in a smart charge mode, where they are charged at time with more wind power and/or low demand. Additionally they are analysed in a vehicle to grid mode (V2G).

For the total charging capacity is 18 kW per vehicle, corresponding to a total of 8,482 MW for both charging and discharging. The total battery capacity of 500.000 vehicles is 11 GWh. For 500.000 hybrid HFCVs the total battery capacity is 3.9 GWh. When using the V2G for charging and discharging to the grid, the losses are 7 per cent in both the grid to battery mode and the battery to grid mode.

D.3 Future concept vehicles

In this part a number of different technological Electric Vehicles (EVs) trajectories used in the analysis are defined.

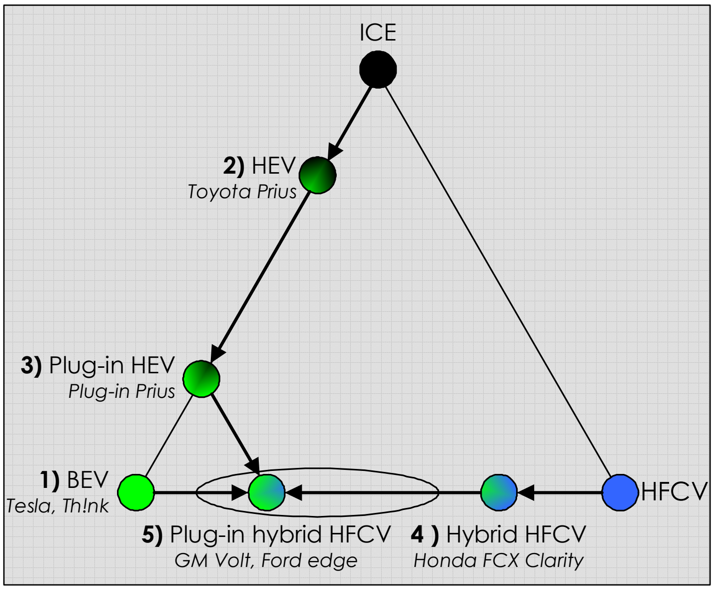
The Electric Vehicles (EVs) trajectories include Battery Electric Vehicles (BEVs) and Hydrogen Fuel Cell Vehicles (HFCVs). A number of different Hybrid Electric Vehicles (HEVs) are defined, including Plug-in Hybrid Electric Vehicles (plug-in HEVs), Hybrid Hydrogen Fuel Cell Vehicles (Hybrid HFCVs) and Plug-in Hydrogen Fuel Cell Vehicles (Plug-in hybrid HFCV).[92]

A BEV is in the analysis defined as a vehicle that can be partly of fully driven by batteries with focus on Li-ion technologies. Three different BEV are used in this report. That is FPBEV, HEV and PHEV. A FPBEV is a BEV with only one drive train – an electric motor, and is fully capable of freeway driving. A HEV is a car that has two drivetrains – an Internal Combustion Engine (ICE) and an electric motor. The battery is rather small (in KWh terms) and is used for accelerations and regenerative braking. A Toyota Prius is a HEV. A PHEV is a HEV with a bigger battery that can run on electricity from the battery alone. The battery can be charged from the electricity grid, hence the name plug-in hybrid vehicle.

A FCV is in this report defined as a vehicle that can be partly or fully driven by fuel cells. In this report focus is on the Proton Exchange Membrane Fuel Cell (PEMFC) technology. All FCVs as of today use some kind of electric energy storage (Super Capacitors (SCAPs) or batteries) for accelerating and capturing the braking-energy. FCHVs are defined as having some kind of electric energy storage. The energy storage assists the FC when accelerating and store electric energy when braking for later use. Since all FCVs have some kind of energy storage as of today all FCVs are oer definition FCHVs. A PFCHV is a FCHV with a battery that can be charged from the grid. As for the PHEV a PFCHV can run on electricity from the battery alone.

In order to fully understand what a plug-in hybrid HFCV is capable of today a BEV, a HEV a plug-in HEV and a hybrid HFCV is defined and described.

Figure 21 – Plug-in hybrid HFCV and its coherence to other vehicle types



On basis of the findings a, so far non existing, plug-in hybrid HFCV, where the best parts of the other cars are used, has been constructed/fabricated. The methodology used is seen in the figure to the left. The idea is to use findings regarding cars that have similarities to the plug-in hybrid HFCV that is to be analysed. In theory a plug-in hybrid HFCV have similarities to a BEV, a plug-in HEV and a HFCV.

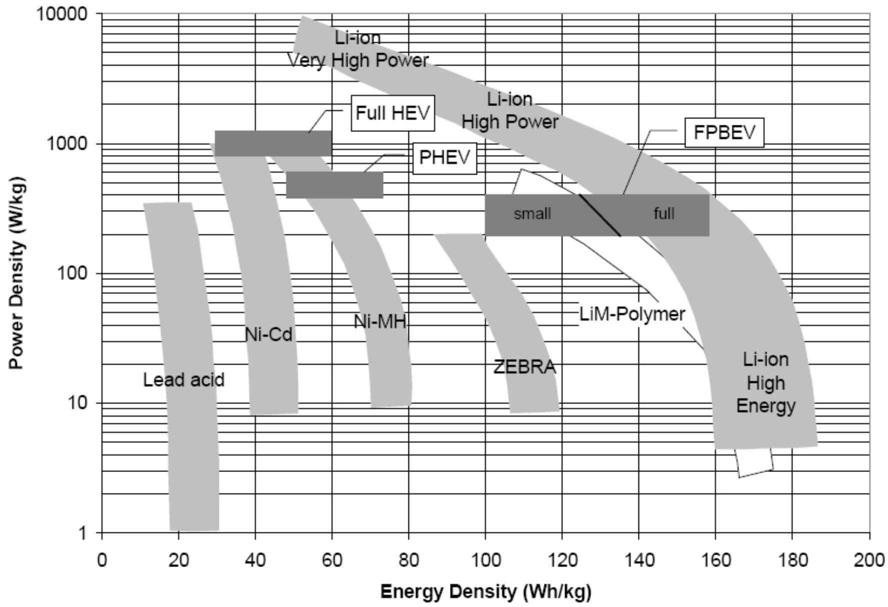
The easiest way to construct a future plug-in hybrid HFCV is to combine the energy chains for BEV and HFCV.

The term Plug-in hybrid HFCV is very long. It has therefore been decided that for the rest of this report the term hybrid HFCV is in fact a plug-in hybrid HFCV.

D.3.1 Full Performance Battery Electric Vehicle

According to California Air Resource Board (CARB)[93] only a few battery types have the potential to meet the combination of power and energy requirements for full Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Full Performance Battery Electric Vehicles (FPBEVs) as illustrated in the figure below.

Figure 22 – Potential of Battery Technologies for HEV, PHEV and EV applications



The figure includes the general relationship between gravimetric power and energy densities for the battery types used or being considered for automotive applications. These so-called Ragone plots show that, for each type, batteries designed for high power densities have substantially lower energy densities than batteries optimized for high energy (FPBEV designs). The figure indicates that only lithium ion batteries can be designed to meet the performance requirements of small and midsize FPBEVs, all types of PHEVs, and full HEVs.

Of the reasons stated above the only battery type analysed is li-ion batteries in future BEV applications. Concerning the price for the car itself, the weight algorithms, and the energy consumption algorithms pr. km, the data origins from "Alternative drivmidler i transportsektoren – COWI beregningsmodel" and algortithms from Kaj Jørgensen, Risø.

A price of $ 240 – 280 / KWh for Li-ion batteries, at a yearly production rate of 2500 MWh / year, is by CARB[94] assumed to represent the Li-ion manufactures specific cost projections for Li-ion modules using 45 Ah high energy-design cells.

It has to be noted that prices are only indicative since it is very hard (almost impossible) to give precise predictions about prices of Li-ion batteries in a far future. Material consumption, material price, production rate, cell, module and battery pack design, economics-of-scale cost reduction factor, mark-up etc. all contribute to a very high degree of uncertainty concerning the cost of Li-ion batteries in the future.

The production of 2500 MWh / year corresponds to an annual production rate of 100.000 batteries of 25 KWh capacity pr. battery. In order to keep things simple a uniform price of 250 USD / KWh is used.

In the table below theoretical FPBEV with ranges ranging from 0 – 600 km at 100 km intervals are listed. It has to be noted that heating and/or air-condition is not included. Furthermore it has to be noted that the range is based on new batteries and usage according to NEDC.

Table 20 – Theoretical characteristics of FPBEV with different ranges

Range (km)	0	100	200	300	400	500	600
Battery size (KWh)*	0	10,5	22,0	34,2	47,1	60,5	74,5
Weight of car (kg)	1.049	1.049	1.049	1.049	1.049	1.049	1.049
Weight of battery (kg)	0	97	168	238	307	376	445
Charging time**	0	0,6	1,24	1,93	2,66	3,42	4,21
Energyuse (Wh/km)*	98	105	110	114	118	121	124
Batteryprice (DKK)***	-	17.375	36.267	56.414	77.633	99.809	122.843
Carprice excl. batt. (DKK)*	87.000	87.000	87.000	87.000	87.000	87.000	87.000
Carprice incl. batt. (DKK)*/***	87.000	104.375	123.267	143.414	164.633	186.809	209.843

* = Based on algorithms from Kaj Jørgensen, Risø and "Teknologikataloget", summer tires, heater/aircon off.
** = Assuming 3-phased 380 V, 16 A power socket
*** = CARB, Kalhammer, and at 6,6 DKK / USD (as used in Teknologikataloget)

In the above table it is seen that the reference FPBEV not only become more expensive as a function of range pr. charge, it also becomes heavier and therefore uses more energy pr. km driven. It has to be noted that weight increases due to heavier batteries are included but that second order weight increases due to the heavier battery such as larger electric motor, larger springs, stronger frame etc. is not included. These 2nd order weight increases result in even higher energy consumption pr. km driven for the FPBEV with ranges of 300, 400, 500 and 600 km than listed above. Better insight and algorithms are needed in order to include these 2nd order effects. It hasn't been possible to find any information regarding the magnitude of these 2nd order effects but they are considered to be at a considerably magnitude. The reference gasoline car in comparison costs 77.000 DKK.

If 4 extra passengers each weighing 68 kg and carrying 7 kg of luggage (300 kg all in all)[95], then the energy-consumption pr. km can be expected to increase from 110 to 134 Wh/km. The range is thereby reduced from 200 to 164 km. It has to be noted that the reference car has a gross vehicle weight of 1.850 kg and an average driving vehicle weight of 1325 kg. The maximum payload is thereby 525 kg, which is significantly more than the above stated 300 kg. At maximum payload the expected energyuse has increased to 145 Wh/km and thereby reduced the range to 151 km.

At the Paris Auto Show held in October 2008 a number of different fully BEV where presented. The vehicles have been grouped into five categories, alternative-, cheap-, city-, full-size- and sport vehicles. The alternative-, the cheap- and the sport vehicles are excluded from the analysis. The alternative and cheap vehicles are not included in the analyses as it assumed that these cars won't fulfil the expectations car buyers have. Finally the sports vehicles are excluded from the analysis because these cars are too expensive to the majority of the Danish population. In the table below a summary of the different cars can be seen.

Table 21 – Specifications on BEV at Paris Auto Show October 2008

Cartype	# of producers	Battery technology	Km/hr	Range (km)	Average range (km)
Cheap	4	Li-Pol/LiFePo4/ Zebra/?	64 – 90	80 – 120	82
City	6	Li-ion	105 – 140	80 – 400*	186
Full-size	3	Li-ion/Li-ion + SCAP	110 – 130	150 – 250	200
Sports	2	Li-ion/Li-Pol	150 – 201	290 - 354	321

* Only the Heuliuz Will, which comes with three different battery-sizes have a range of more than 160 km.
Source: Paris motor show Oct. 2008, H2 Logic data collection.

The average range of the city-vehicles are 186 km, and the average range of the full-vehicles are 200 km. A weighted average of the two categories "city" and "full-size" result in an average range of 190 km. The FPBEV used in the analysis is set to a range of 200 km as measured in NEDC.

D.3.1.1 Tear of batteries when used to balance the grid

In order to estimate the cost of using batteries for balancing on an hourly basis one needs to take the lifetime for batteries measured in hours and divide by the cost of the systems.

Optimally each part of a car has the same lifetime that is the motor of today's cars are worn op at the same time as the gears, the suspension, the frame etc. This naturally also applies to BEV, HFCV and hybrid HFCVs of the future.

In this subsection batteries for the use in BEV with a range of 200 km, batteries for the use in hybrid HFCVs with a battery range of 60 km is analysed.

Since an average gasoline car drive 175.000 km and an average diesel car drives 275.000 km before scrapping. At 200 km pr. charge and 100% DoD this means that the batteries in a BEV have to be able to be charged 875 times in order to drive the same distance as a gasoline cars and 1.375 times in order to drive the same distance as a diesel car. This is the absolute minimum requirement for batteries on this parameter. Some batteries (e.g.) SAFT and A123 batteries can last for minimum 600.000 km assuming 100% DoD and a range of 200 km in a BEV (see the table below). There is a high probability that the batteries will outlast the car. The tear on the batteries when using them for hybridization the electricity grid can therefore be expected to be small. As earlier stated 350.000 and 550.000 km is the assumed design life of a gasoline and a diesel car respectively. Assuming 550.000 km of design life, then battery capacity above 550.000 km can be considered as free. In the case of SAFT batteries the free capacity is 50.000 km or 250 100 % DoD. Assuming a life expectancy of 15 years this is equal to 16 – 17 100 % DoD pr. year. When using the same battery for shallow cycles one has a free capacity of 5.450.000 km or 908.333 3 % DOD (6 km pr. cycle). Assuming a life expectancy of 15 years this is equal to 166 3 % DoD pr. day. It seems as if the SAFT batteries on this particular parameter are over designed. A123 cells on the other hand are designed for 100 % DoD. These cells has a much longer life expectancy than SAFT at 100 % DoD (1,4 mio. km vs. 0,6 mio. km), but has a lower life expectancy when used in shallow cycles (1,44 km vs. 6,0 mio. km).[96]

Table 22 – Life expectancy in km for a 200 km range BEV

	SAFT		A123	
	Cycles	km eq.	cycles	km eq.
Deep cycles (100 % DOD)	3.000	600.000	7.000	1.400.000
Shallow cycles (3% DOD)	1.000.000	6.000.000	240.000	1.440.000

Using the same batteries in a plug-in hybrid HFCV gives some quite other numbers.

Table 23 – Life expectancy in km for the battery in a plug-in 60 km hybrid HFCV

	SAFT		A123	
	Cycles	km eq.	cycles	km eq.
Deep cycles (100 % DOD)	3.000	180.000	7.000	420.000
Shallow cycles (3% DOD)	1.000.000	1.800.000	240.000	432.000

From Table 23 it seems as if the life expectancy in this configuration is in the low range of what is needed (except for SAFT batteries and shallow cycles). Either better batteries are needed, the 550.000 km lifetime assumption have to be loosened, larger batteries have to be used in order to have free capacity that can be used to hybridize the electricity grid or the definition of EOL for batteries (80 % SOC at EOL compared to BOL) have to be loosened.

D.3.2 Hybrid Electric Vehicles

The by far most sold Hybrid Vehicle world wide to date is the Toyota Prius. The latest generation of the Toyota Prius (generation III) uses NiMh batteries that has an energy density of 46 Wh/kg, each module weighs 1,04 kg and there are 28 modules. The combined energy is therefore 1,34 KWh.[13]

D.3.3 Plug-in Hybrid Electric Vehicles

It has become increasingly popular to upgrade HEV with a bigger battery pack. At least 7 companies sell at commercially terms conversion kits for hybrid cars such as the Toyota Prius in the US.[97] The company HyMotion is one of the leading of these companies. HyMotion who is owned by A123 and use A123 cells, sell a 5 KWh battery pack to end customers for 9.995 USD including installation. The product specifications are;

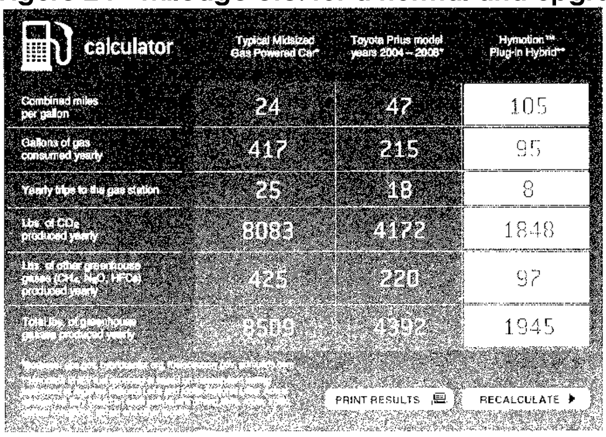
Designed for Toyota Prius, model years 2004 – 2009
~ 5 kWh pack , 5.5 hour charge time, ~ 180 pounds
Up to 100 mpg for 30-40 miles within electrically assisted driving range
Crash tested to federal new vehicle standards
$9995 – includes 3 year standard warranty and installation

In the figures below a picture of the battery pack and a print from HyMotions homepage showing how many miles one can expect to drive on one gallon of gasoline is showed assuming;

- 50 % city and traffic & 50 % highways and open road
- 20 miles pr. one way daily commute
- Possible to plug in at work and
- 10.000 miles (16.093 km)/yr

Figure 23 – Picture of the ~ 5 KWh HyMotion battery

Figure 24 – Mileage etc. for a normal and upgraded Prius



calculator	Typical Midsized Gas Powered Car*	Toyota Prius model years 2004 – 2008*	Hymotion™ Plug-in Hybrid**
Combined miles per gallon	24	47	105
Gallons of gas consumed yearly	417	215	95
Yearly trips to the gas station	25	18	8
Lbs. of CO_2 produced yearly	8083	4172	1848
Lbs. of other greenhouse gases (CH_4, N_2O, HFCs) produced yearly	425	220	97
Total lbs. of greenhouse gases produced yearly	8509	4392	1945

PRINT RESULTS RECALCULATE

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13 46 Wh/kg * 1,04 kg/module * 28 modules.

The Hymotion PHEV fuel economy is based on independent testing performed at Argonne National Labs and Idaho National Labs. Actual mileage will vary based on each individual's driving style, route, traffic, climate conditions, terrain and other factors.[98] The 47 and 105 miles/gallon for the "Toyota Prius model years 2004 – 2008" and the "Hymotion Plug-in hybrid" is equal to 20,0 and 44,6 km/l respectively. In the above figures it has been shown that significantly lower fuel consumption can be achieved if one upgrades a hybrid car to a plug-in hybrid car with a bigger battery. An improvement of a factor of 105 miles/gallon / 47 miles/gallon = 2,23 is achieved. The combined size of the 1,34 KWh and 5 KWh battery packs is 6,34 KWh.

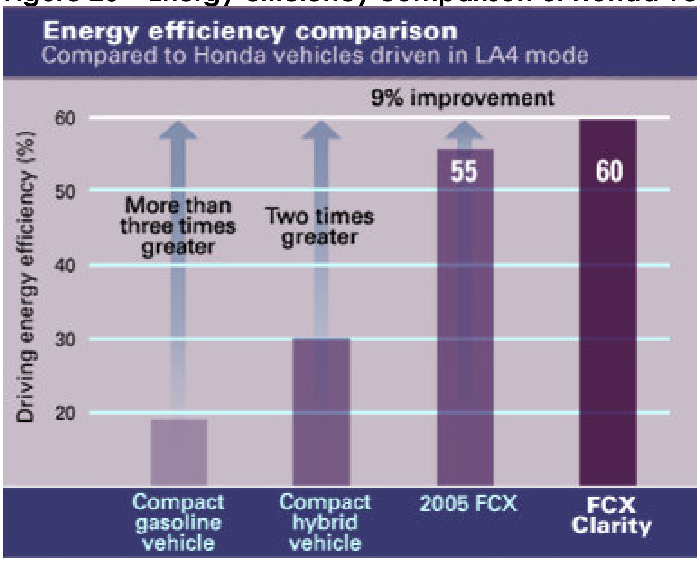
D.3.4 Fuel Cell Hydrogen Vehicle

Honda FCX Clarity is, to the knowledge of the author, the FCHV that have achieved the world's highest TTW efficiency. According to the official Honda FCX Clarity homepage the Honda FCX Clarity has a "driving energy efficiency" of 60 % driven in LA4-mode. It is assumed that "driving energy efficiency" is the same as TTW efficiency. It is also assumed that the State-Of-Charge (SOC) is the same before and after the drive-cycle has been performed. In the table below the expected efficiencies for the major components are listed.

Table 24 – Expected efficiencies of the Honda FCX Clarity

What	Expected efficiency	Sources
Expected electric motor efficiency	~ 0,97	99
Expected regenerative efficiency	~ 0,15	100
Expected FC-system efficiency (LA4-mode)	~ 0,54	Estimated
Tank-To-Wheel calculated efficiency	~ 0,54 * ~ 0,97 * (1 + ~0,15) = ~ 0,60	Estimated
Honda official Tank-To-Wheel efficiency	~ 0,60	101

Figure 25 – Energy efficiency comparison of Honda vehicles driven in LA4 mode



The energy consumption in LA4-mode, of which the Honda FCX Clarity is tested upon, has to be compared to the energy consumption in New European Drive Cycles (NEDC)[102] in order to have an idea about the energy efficiency according to European test methods. In both drive cycles (LA4 as well as NEDC) the average energy consumption is very low. "For the 2002 state-of-the-at technology and on the NEDC cycle, the average power developed by the vehicle for propulsion is around 4 KW".[103] Since the average speed is lower for the LA4-mode (31,5 km/hr in average compared to 33,6 km/hr in average for NEDC) the power consumption is therefore expected to be marginally lower.[104] The expected average power consumption in LA4-mode is expected to be somewhere between 3,5 and 4,0 KW. For a Honda FCX clarity the difference between 3,5 and 4 KW is very small when the FC-system can deliver 100 KW. It is therefore assumed that the efficiency difference is of no importance. In both driving cycles of 60 per cent efficiency is assumed.

The numbers for the efficiency of the FC-system is in line with the best polarization curves known for PEMFC, assuming low power consumption for the fuel cell system itself.

It has to be noted that the data's from Honda can only be verified when Honda decides to publish more detailed information about their Honda FCX Clarity.

It is assumed that a fuel cell system for the use in a vehicle can increase or decrease the power output but 15 KW/s.[105] It is therefore assumed that this will not pose a bottleneck for the ability to provide balancing power and/or energy for the electric grid.

D.3.5 Hybrid Fuel Cell Vehicle

A hybrid Fuel Cell Hydrogen vehicle (hybrid HFCV) can be regarded as a PHEV where the gasoline tank and the ICE are replaced by a hydrogen-tank and a FC system. Batteries and FCs can to a large extent be regarded as complementary technologies.

In a FCV the advantages of using batteries are the possibility to use the batteries for accelerating, regeneration and if the battery is of a certain size, to use the FC at a point of the polarization curve with a high electric efficiency.

The advantages of using FC in a BEV are a lower weight of the car and thereby a lower energy consumption pr. km driven, the possibility to use heat from the fuel cell stack to heat and/or cool the cabin compared to the BEV where the heat has to come from the battery, much faster refueling and a considerable longer range between refueling/charging. The hybridization advantages are seen in the table below.

Table 25 – Advantages of using batteries in a FCV and of using FC in a BEV

Advantages of using batteries in a FCV	Advantages of using a fuel cell system in a BEV
- Recover kinetic energy during braking phases - To assist the fuel cell system during fast power transits - To operate the fuel cell in the high efficient power range - The FCS in a FCHV can be designed with a fewer KW	- Faster refuelling (~ 3 min vs. 1/6 – 4 hrs) - Much longer range (especially if cold or hot) - Lower weight of energy system and thus a lower energy consumption pr. km (Wh/km) - Heat utilization from FC-waste heat increases the range dramatically (heat and aircon.)

Because of the advantages of using batteries in a FC system there seems to be a trend from FCHVs with a very small hybridization (in terms of KWh) towards vehicles with increasing larger batteries.

It wasn't until 31st of January 2007 that Ford revealed what they term as the worlds first "Plug-in Fuel Cell Vehicle".[106] Therefore there hasn't been published much about this concept in scientific articles etc. Especially there hasn't been published much about the combined efficiencies that can be obtained today if State-of-the-art technologies are combined in the right way. The most prominent proponent for this hybridization strategy is most likely the GM Volt that has a battery-electric range of 40 miles (64 km).

A higher share of the fuel cell cars can be expected to be plug-in hybrid cars compared to plug-in gasoline hybrids since;

the electric motor is the only drive motor in the cars (and not just a relatively small "support" motor as is the case for todays hybrid cars)

a lower batteryprice pr. KWh in the future will make it cheaper to enlarge the batterypack

higher fuel costs and an increased focus on energy efficiencies is likely to result in market as well as political mechanisms that support a higher share of mileage driven on batteries.

On the other hand there is, as stated earlier, an upper limit to how big these batteries because of a long charging time, costs and weight can become. A battery size of approximately 6 – 8 KWh seems to be a good compromise between the different factors. A 7,8 kWh battery is based on excel analysis' used for the further analysis'.

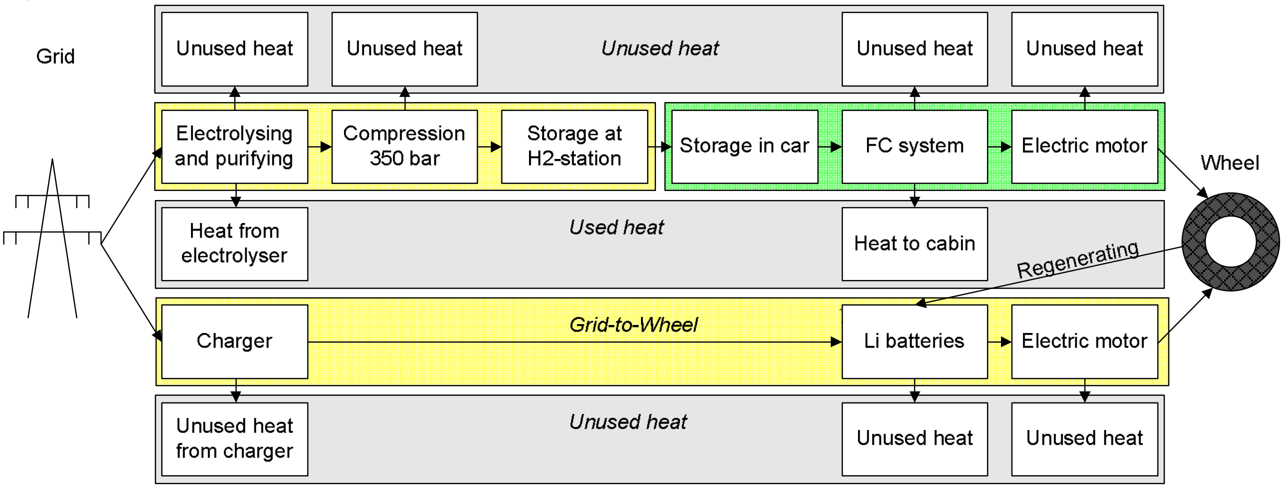
D.3.5.1 Expected real world Hybrid HFCV efficiency

The tank-to-wheel efficiency of any plug-in hybrid car is a result of the efficiency of the one driveline multiplied with the use of this driveline plus the efficiency of the other driveline multiplied with the use of this driveline.

The grid-to-wheels efficiency of the hybrid HFCV is obtained by taking the efficiency for a pure BEV multiply it with the share of km driven on batteries and add the fuel cell system grid-to-wheel efficiency multiplied with the share of km driven on hydrogen. A 90 % efficiency for the battery covering 73 % of the km driven plus a 60 % efficiency for the fuel cell system used for the remaining 27 % of km driven is used in the analysis. The combined efficiency therefore is (0,90*0,73)+(0,60*(1-0,73)) = 0,83. It has to be noted that the actual efficiency in a hybrid FCHV will vary compared to these numbers as a result of actual progresses regarding batteries, fuel cells, weight, Cw-value as well as driving pattern, driving distance, heat and air-condition use etc. Especially using the battery for heat and/or air-condition greatly reduces the overall grid-to-wheel efficiency.

In the figure below the concept Grid-to-wheel for a hybrid HFCV using 350 bars hydrogen is shown.

Figure 26 – Grid-to-wheel



The grid-to-wheel efficiency for the hydrogen part of the equation is 0,44 (0,76 for electrolysing * 0,96 for compression * 0,54 for FC * 0,97 motor-efficiency * 1,15 for regenerating brakes).

multiplying the hydrogen grid-to-tank efficiencies with the grid-to-battery efficiencies to the fuel cell part and the battery part of the above equation respectively. The share is between 0,00 and 1,00 for each track, and when adding the two tracks they have to summarize to 1,00 at each step.

D.3.5.2 Hydrogen refueling

It is assumed that an average hydrogen tank holds 4,2 kg hydrogen and that the tank is ¾ empty when refueled. It is furthermore assumed that the car is fuelled to its capacity, equivalent of 3,15 kg of hydrogen pr. filling. As earlier stated an average of 384 fillings pr. day can be expected at the station. 384 fillings pr. day multiplied by 3,15 kg h2 is equal to 1.210 kg h2/day. Assuming a filling time of 180 sec. for 5 kg of h2 the average filling time will be 113 seconds in average.[107] On top of this there is payment and nozzle-handling. If one assumes a total time of 180 seconds (3 minutes), then a maximum of 20 refuellings can be done per dispenser per hour.

An average Danish car drives appr. 18.000 km/year. Since 27 per cent of the km is assumed to be driven on hydrogen this equals to 4.860 km on hydrogen pr. year. Refuelling from 1,15 kg to 4,2 kg (full capacity) in average when filling is equal to appr. 11 refuellings a year.[14]

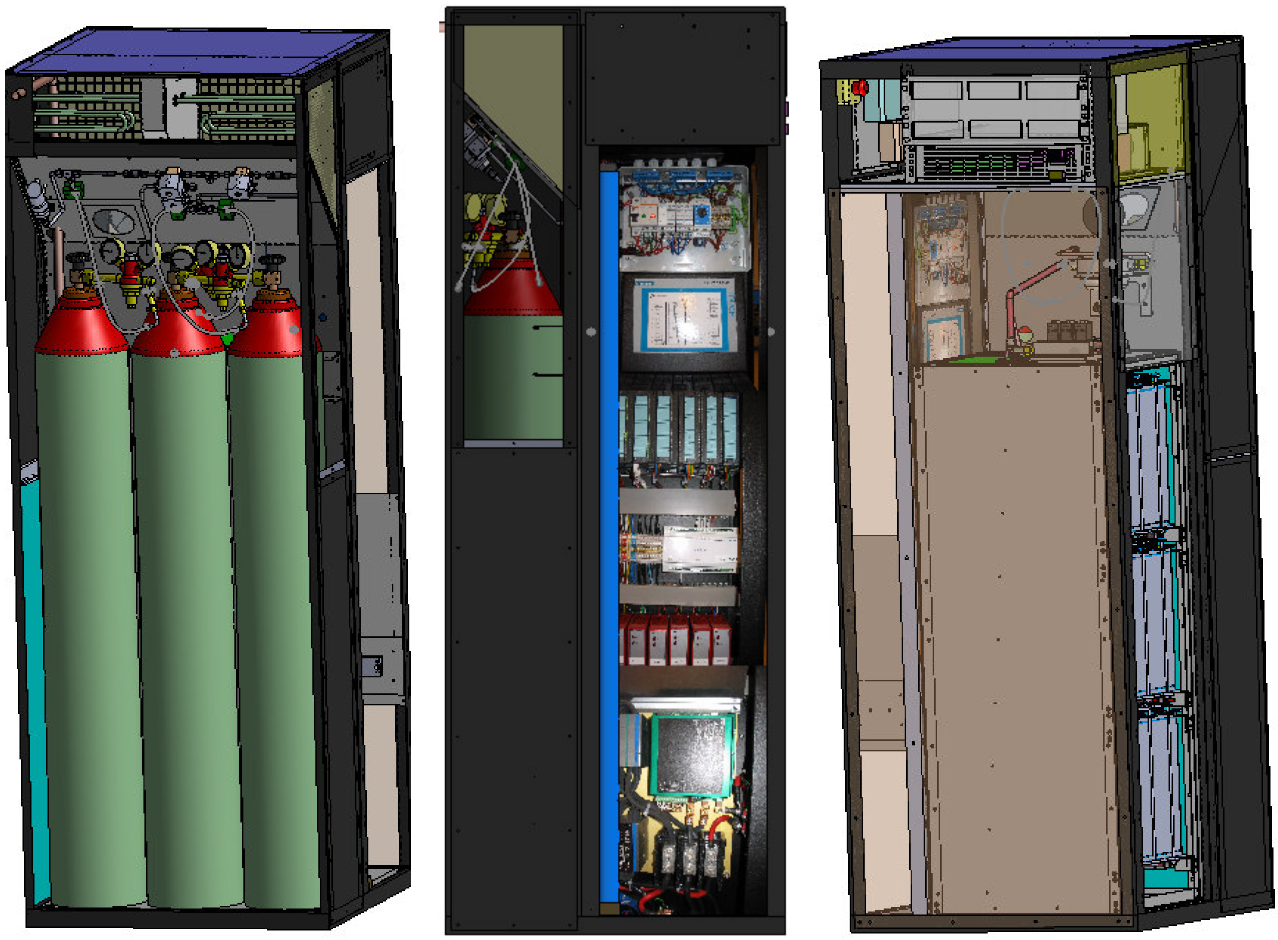
[14] 4.860 km /100 km * 0,7 kg h2/100 km = 34,02 kg h2/year. 34,02 kg h2/yr / 3,15 kg/refuelling = 10,8 refuellings/year.

E. – BALANCING POWER PROTYPE DEVELOPMENT

E.1 Prototype development

In order to enable the fuel cell based power back up system to deliver power to the grid, based on a demand-signal from the utility company, the following development of a prototype is described. This grid balancing prototype was installed in an existing fibre optic infrastructure point (POP), with a fuel cell based power back up system (from the CanDan 1 project).

Figure 27 – CD1 Fuel based power back up system



Front with hydrogen bottles
Right side with electronics
Back and left side with fuel cell stacks

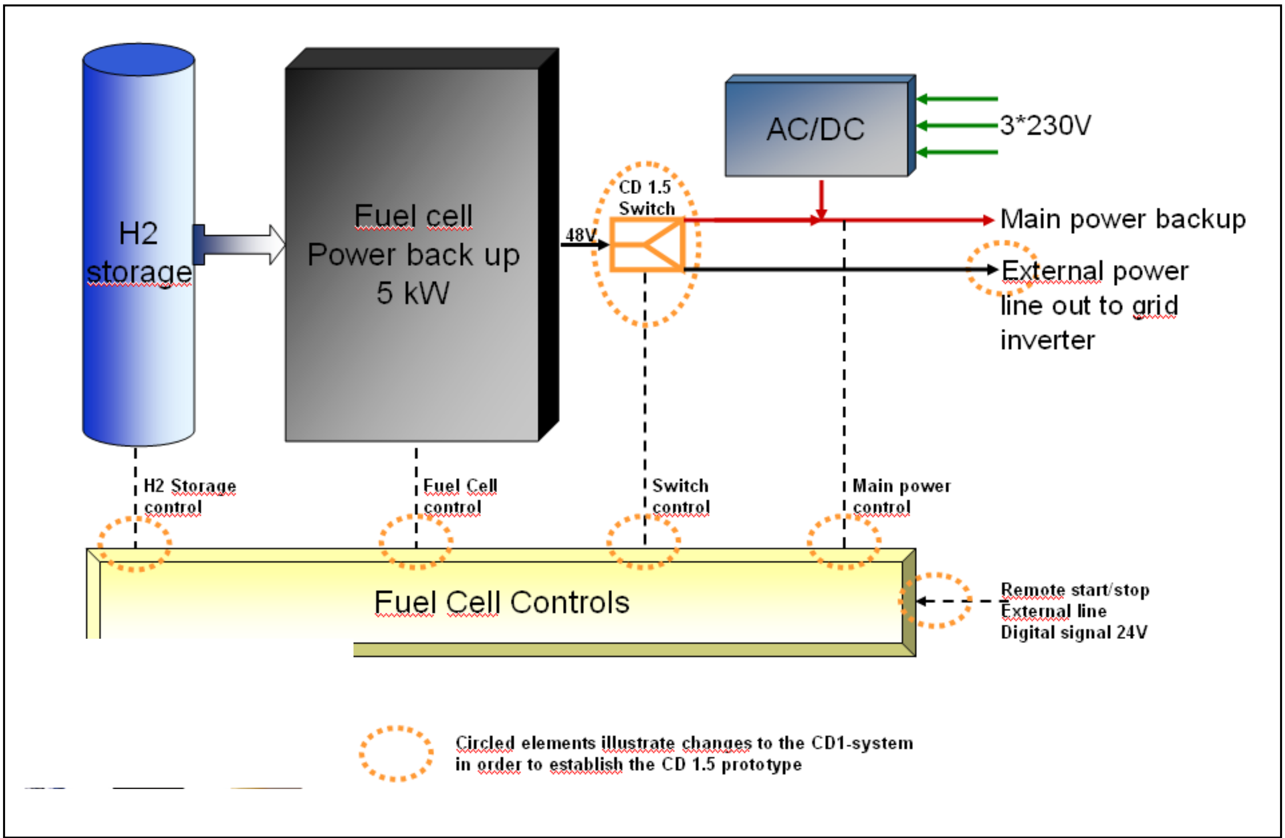
The dimensions of the system are 750*750*2062 mm. It weighs ~289 kilograms ex. H2-bottles. The systems own power consumption is approximately 350 W.

Development of the protype demanded the following modifications and activities:

Rewiring of internal relays in the fuel cell system
Programming of the PLC
Establish new input port on PLC
Installing and saving of the custom programmed operating system.

A sketch of the solution is illustrated in below.

Figure 28 – Sketch of prototype



The inverter applies to the following specifications:

- Input: 48-53 V DC. Max. 100 A (5000 W) Slow start.
- Output: 3*230 V/3*400 V 50 Hz (+/- 0,X Hz) or as decided by end-user.

The prototype requires a communications connection to the fuel cell system to call for power generation to the grid. From the EnergiMidt equipment one single pole relay out (24 V, 1 A) was needed. This relay output port is controlled by EnergiMidt's grid-monitoring system and is connected to the new input port on the fuel cell PLC. Thereby it is possible to signal/control the fuel cell system to deliver power to the grid.

The prototype was built and installed on site while the system is in full operation. To avoid a system outage in case of grid power outage alternative power back up had to be installed before implementation of the prototype.

If the grid goes down while the prototype is operated, a situation occurs where the fuel cell provides power to grid but will need to switch back to supply power to the POP. For this to happen, the inverter drops out, so the fuel cell does not send power in a loop back to the POP. At the same time a utility technician working on the grid should be aware, that this POP has a grid connected power generator installed – possibly providing power onto the grid instead of just drawing power from the grid.

F. – MARKET POTENTIALS AND CONCLUSION

F.1 Stationary applications

The market potential for micro CHP in Denmark is substantial. There are about 2.5 million households in Denmark covering around 280 million m^2.[108] The dominant share of buildings is heated by district heating (around 50%) which is also the fastest growing heating method. Around 1.5 million households live in houses – separate buildings or rows of connected houses. About 400,000 homes are heated by natural gas and the same number of houses is heated by oil-fired boilers. The number of homes with oil-fired boilers is slowly decreasing while the number of houses with gas-heating is increasing. The number of heat pumps is at a low level in Denmark compared to e.g. Norway and Sweden but is increasing. The average heat usage pr. m2/year is decreasing because of better insulation and stricter building regulations.

The average lifetime of an oil-fired boiler is around 15 years. The gas-fired boiler has an average lifetime of about 12 years. Therefore approximately 30,000 boilers of each type are changed every year – either to a new boiler of the same type or to a different heating technology. With built-in multifuel reformation Dantherm Power will be able to technically substitute all these boilers with fuel cell based mCHP systems running on natural gas, oil or methanol besides the readily available hydrogen based cells.

Thus the market could presently be estimated to around 800,000 units. The growing share of district heating along with continuing development of competitive heating solutions and technologies will bring this market potential down over time. Heat pumps, solar panels and solar energy take up only a fragment of the heating in Denmark today.

F.1.2 MicroCHP power balancing potential

It is expected (by Dantherm), that even giving the growing share of district heating and other heating technologies the market potential for mCHP will be half a million households by 2030.

With an estimated average base load in a family household of 50-100 watts a mCHP with 1 KW effect could perform a 0.9 KW balancing power. Given a penetration of 500,000 units of mCHP this balancing power could accumulate to 450 MW. However at a cold winter day the balancing power available will be significantly lower. Further investigations and real world experiences are needed.

F.1.3 UPS power balancing potential

UPS is typically used to protect computers, telecommunication equipment or other electrical equipment from power failures. The potential for using UPS’s for power balancing could thus be estimated based on statistics for installed capacities. This, however, has not been available. Estimating the number of UPS’s in IT-installations seems to be too uncertain to be of value.

In telecommunications networks it is possible to calculate a number of reasonably consistent figures. In Denmark there is presently close to 13,000 mobile communications antennas (base stations) installed. They are installed at around 6,300 different addresses, since some sites have more than one antenna and even some have more than one antenna with different frequencies. In Denmark the usual base station has power back up for a limited time of 15-120 minutes. The necessary capacity for a small station is around 1.5 KW. This would cover around 3,500 base stations. The rest are larger sites with 3-5 KW power consumption. As a consequence the estimated balancing power potential in the base stations of mobile networks in Denmark accumulate to approximately 14 MW (Dantherm estimate).

F.2 Transport technology scenarios

In this part the transport technology scenarios are presented. The technical and economic data are presented for vehicles and for fuelling infrastructure.

F.2.1 Plug-in hybrid HFCVs market penetration

In order to estimate how many hydrogen powered cars there might be in different years, and thereby the hybridization potential, one can take some international studies regarding the number of FCVs and extrapolate the data so they reflect Danish conditions. Three sets of data, an American and two European reports, are used. The three reports are;

"Analysis of the Transition to hydrogen fuel cell vehicles & the potential hydrogen energy infrastructure requirements" an analysis conducted for the U.S. Department of Energy, published March 2008 and commented upon by the oil and car industry in the US.[109]

"HyWays – The European Hydrogen Roadmap" an analysis conducted for the European Commission, published February 2008 in cooperation with the car & oil industry.[110]

"The economics of a European hydrogen automotive infrastructure", a study performed for one of the worlds leading hydrogen suppliers as of today, Linde AG.[111]

As of end of 2008 less than 1.500 hydrogen cars have been manufactured worldwide[112], and in 2008 less than 500 cars where produced. In comparison factories exists that produce 3.000 ICE cars pr. day.[113] These numbers illustrate that development are still at a very early stage in the diffusion of hydrogen cars.

Several factors influence the results when extrapolating the different EU and US studies to Danish conditions. The most important factor is the year HFCVs are introduced, the second most important factor is the maximum penetration rate (in percentages of total vehicle fleet) and finally the pace of which hydrogen vehicles are introduced is of great importance.

All three studies assume technological as well as economical targets to be met at certain times. On top of this political support is assumed in the US and the HyWays studies. Finally the HyWays study is the only of the three studies to analyse upon significantly higher prices on fossil fuels.

F.2.1.1 US DOE studies

The US DOE study operates with three vehicle penetration scenarios:

- **Scenario 1** – Production of thousands of vehicles per year by 2015, and hundreds of thousands by 2019. This option is expected to lead to a market penetration of 2 million FCVs by 2025.
- **Scenario 2** – Production of thousands of FCVs by 2013 and hundreds of thousands by 2018. This option is expected to lead to a market penetration of 5 million FCVs by 2025.
- **Scenario 3** – Production of thousands of FCVs by 2013, hundreds of thousands by 2018, and millions by 2021, such that market penetration reaches 10 million FCVs by 2025.

Table 26 – Deployment of hydrogen fuel cell vehicles in USA (thousands)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Scenario 1	0	0	0	3	4,8	7,2	50	100	150	200	250	300	400	500
Scenario 1 Cum.	0	0	0	3	7,8	15	65	165	315	515	765	1065	1465	1965
Scenario 2	0,5	1	1	30	60	60	200	300	400	500	600	700	900	1000
Scenario 2 Cum.	0,5	1,5	2,5	32,5	92,5	153	353	653	1053	1553	2153	2853	3753	4753
Scenario 3	0,5	1	1	30	60	60	300	500	750	1000	1200	1500	2000	2500
Scenario 3 Cum.	0,5	1,5	2,5	32,5	92,5	153	453	953	1703	2703	3903	5403	7403	9903

To extrapolate the US. Deployment scenarios to a Danish context one has to take a number of different factors into account, such as;

the number of inhabitant
the number of cars pr. 1.000 inhabitants
Purchasing Power Parity (PPP) pr. inhabitants
Inequality (e.g. measured by the Gini-coefficient)

It is assumed that the PPP, inequality and other factors outbalance each other in the two countries. The only two factors analysed are therefore the number of inhabitants and the number of cars pr. 1000 inhabitants. As of July 2008 the population of USA and of Denmark was 303,8 and 5,411 millions respectively. As of January 2005 the number of cars pr. 1.000 inhabitants was 776 and 354 cars in USA and Denmark respectively.[114][115] If one assumes that the growth rate of cars per 1.000 inhabitants will be the same in Denmark as used in the American analysis, the extrapolation of the American numbers to Danish conditions results in an expected yearly and cumulative deployment as seen in the table below.

Table 27 – Deployment of hydrogen fuel cell vehicles in Denmark (thousands)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Scenario 1	-	-	-	0	0	0,1	0,4	0,8	1,2	1,6	2,1	2,5	3,3	4,1
Scenario 1 Cum.	-	-	-	0	0,1	0,1	0,5	1,4	2,6	4,2	6,3	8,8	12,1	16,2
Scenario 2	0	0	0	0,2	0,5	0,5	1,6	2,5	3,3	4,1	4,9	5,8	7,4	8,2
Scenario 2 Cum.	0	0	0	0,3	0,8	1,3	2,9	5,4	8,7	12,8	17,7	23,5	30,9	39,1
Scenario 3	0	0	0	0,2	0,5	0,5	2,5	4,1	6,2	8,2	9,9	12,4	16,5	20,6
Scenario 3 Cum.	0	0	0	0,3	0,8	1,3	3,7	7,8	14,0	22,3	32,1	44,5	61,0	81,6

F.2.1.2 Europe Linde studies

In the Linde study two vehicle penetration scenarios are listed. The scenarios are seen in the table below.

Table 28 – Expected numbers of hydrogen cars in EU (millions)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
High uptake	0	0,03	0,28	0,73	1,2	1,9	2,86	4,26	6,09	8,17	10,7	13,65	16,84	20,24	24,1	28,19	32,47	36,76	41,2
Low uptake	0	0	0	0	0,02	0,22	0,58	0,94	1,3	1,7	2,47	3,55	4,63	5,73	7,02	8,46	9,92	11,57	13,54

In order to extrapolate the Linde scenarios to a Danish context one basically has to take the same factor into account as for the American study. It is assumed that the penetration numbers in the Linde scenarios can be transferred to the Danish case by taking into account the number of inhabitants in EU and DK and the number of cars in EU and DK.

The extrapolation of the European numbers to Danish numbers results in the following expected cumulative deployment.

Table 29 – Expected numbers of hydrogen cars in Denmark (thousands)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
High uptake	-	0,3	2,4	6,3	10,4	16,4	24,7	36,7	52,5	70,5	92,3	118	145	175	208	243	280	317	355
Low uptake	-	-	-	-	0,2	1,9	5,0	8,1	11,2	14,7	21,3	30,6	39,9	49,4	60,6	73,0	85,6	99,8	117

F.2.1.3 Europe HyWays studies

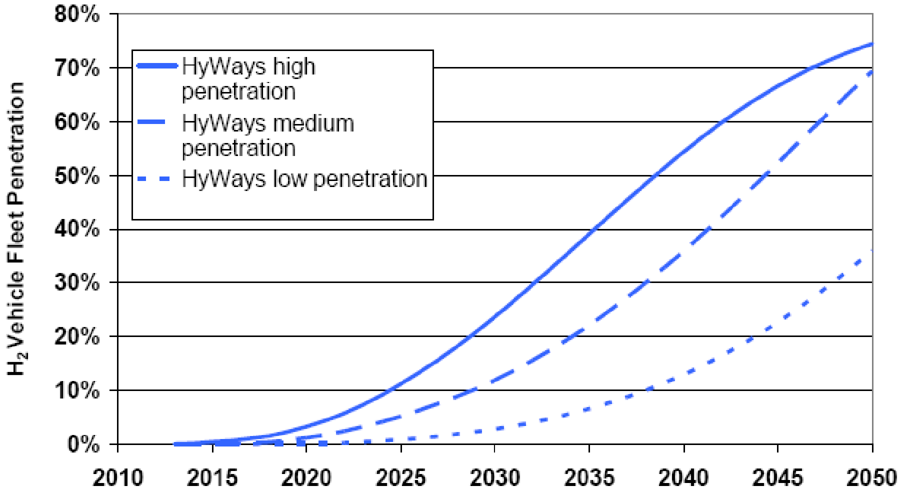
In the HyWays study is listed 6 vehicle penetration scenarios. Three of these scenarios are seen in the table below.[116]

Table 30 – Potential development of hydrogen vehicles share in vehicle stock

Total share of fleet	2010	2020	2030	2040	2050
High penetration	-*	3.3%	23.7%	54.4%	74.5%
Medium penetration	-*	1.2%	11.9%	35.9%	69.4%
Low penetration	-*	0.1%	2.8%	12.9%	36.0%

* Demonstration vehicles and fleets only

Figure 29 – HyWays penetration scenarios of hydrogen vehicles



In order to extrapolate the HyWays scenarios to a Danish context one basically has to take the same factor into account as for the American numbers. The European numbers are however disclosed in % whereas the American numbers are stated in number of cars. Since percentages are not influenced by the differences in cars pr. 1000 inhabitants in the different countries one should not include this factor when extrapolating the European percentages to Danish numbers. It is assumed that the penetration percentages in the HyWays scenarios can be transferred directly to the Danish case. It is also assumed that the demand for transportation that HyWays use[117] is the same that DTF use for Denmark. It is assumed that the PPP, inequality and other factors outbalance each other. In order to get the Danish scenarios of FCHV the HyWays percentages are multiplied with the expected number of cars in DK in 2010, 2020, 2030, 2040 and 2050. The number of cars until 2030 is derived from data from DTF.[118]

The extrapolation of the European percentages to Danish numbers results in the following expected cumulative deployment.

Table 31 – Potential development of hydrogen vehicles in Denmark (thousands)

Total share of fleet	2010	2020	2030	2040	2050
High penetration	*	82,5	634	1.608	2.422
Medium penetration	*	30,0	319	1.061	2.256
Low penetration	*	2,5	74,9	381	1.170
Expected number of cars*	2.264	2.500	2.676	2.956	3.250

* DTF until 2030. Own estimations 2040 and 2050.

It is assumed that the numbers for HFCVs in the US DOE, the Europe Linde and the Europe HyWays study can be converted to plug-in hybrid HFCVs.

In the table below the numbers from the three studies are summarized. It is seen that the studies use different years in their analyses'. It is therefore rather difficult to get a clear idea of the level the studies expect in comparison to each other.

Table 32 – Overview of the possible FCV penetration in DK

Study	Scenario	2012	2013	2014	2015	2016	2017	2018	2019	2020	2030	2040	2050
USA	Scenario 1 Cum.	-	-	-	0,0	0,1	0,1	0,5	1,4	2,6			
	Scenario 2 Cum.	0,0	0,0	0,0	0,3	0,8	1,3	2,9	5,4	8,7			
	Scenario 3 Cum.	0,0	0,0	0,0	0,3	0,8	1,3	3,7	7,8	14,0			
Linde	Low uptake	-	-	-	-	0,2	1,9	5,0	8,1	11,2	117		
	High uptake	-	0,3	2,4	6,3	10,4	16,4	24,7	36,7	52,5	355		
HyWays	Low pen.									2,5	74,9	381	1.170
	Medium pen.									30,0	319	1.061	2.256
	High pen.									82,5	634	1.608	2.422
	Expected # of cars	2.331	2.358	2.380	2.402	2.420	2.440	2.459	2.479	2.500	2.676	2.956	3.250

The various numbers are plotted on curves as numbers and percentages in the figures below. From the figures it can be seen that market penetration of HFCV vehicles in Denmark in 2025 may range from ~ 0,5 % to ~ 7%.

Figure 30 – Cumulative number of HFCVs in Denmark 2010 – 2025

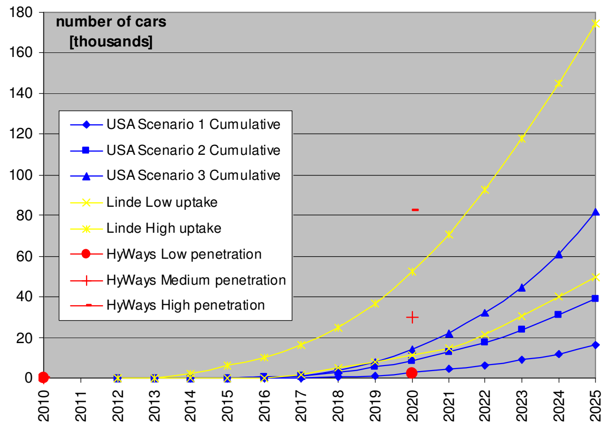
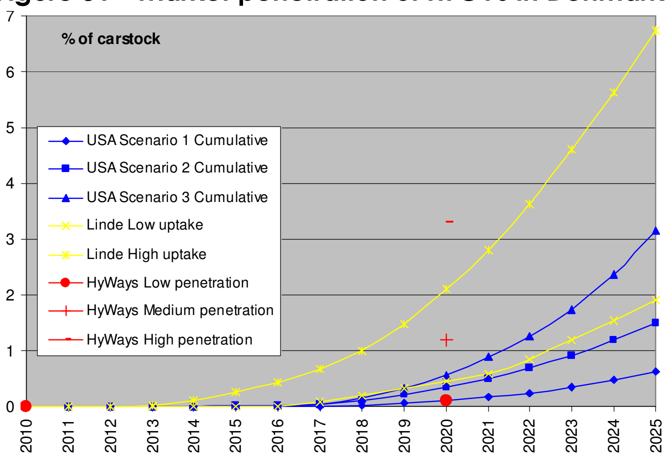


Figure 31 – Market penetration of HFCVs in Denmark 2010 – 2025 in %



The pace of which HFCVs can be introduced at a local level can however be quite different than the introduction at a regional or international level. At a regional and international level the speed at which HFCVs can be introduced is a result of the production of factories, their production capacity, prices etc. At a local level, which Denmark must be regarded as being, the speed at which HFCVs can be introduced is on the other side primarily a result of political decisions and local conditions. In 1999, the first year the Toyota Prius was sold on the American market the San Francisco area accounted for 30 per cent of Prius sales, compared to 6 per cent for all other Toyota models.[119] In other words 5 times more Prius' where sold in the San Francisco area compared to what could be expected based on the sales of other Toyota models.

Denmark has been the first country to generate more than 5, 10 and 15 per cent of the electricity usage from wind power, and has in this field been a true innovator. In other areas Denmark has however been very slow to adapt new technologies. For example as of January 2008 only 7 Toyota Prius' had been sold in Denmark.[120] In 2008 38 Toyota Prius' has been sold in Denmark.[121] If Toyota had sold Prius' according to the number of cars in Denmark compared to the worlds car fleet there would be app. 2.800 Prius' on the Danish streets as of 1st. of January 2008.[15] Whether Denmark will be an innovator, early adopter, early majority, late majority or even a laggard when it comes to the introduction of FCVs are yet to be seen. So far Denmark however seems to have some of the best framework conditions in the world. Denmark has the highest taxes on cars in general. In short there is a 180% tax and 25 % VAT on cars. However until 31.12.2012 there is no tax on BEV and FCV in Denmark.[122] The S-curve for FCVs in Denmark therefore might be even steeper than outlined.

As seen from the above comparison of the numbers from the three studies it is virtually impossible to make valid forecast about the number of HFCVs in the future. For the analysis of grid balancing potential a fixed number of 500.000 vehicles are introduced and used.

F.2.2 Power and energy balancing potential

By multiplying the average size of the fuel cell system with the numbers of cars (500.000) one gets the theoretical hybridization potential. There is however a bottleneck consisting of the size of the power outlet used. If it is assumed that the average size of a power outlet used in a FCV is a 3-phased, 230 Volt and 16 Amp socket. This is equal to 11 KW pr. power socket. In the table below the theoretical hybridization potential is seen. In order to bid as a balancing entity one has to be able to supply and/or receive 10 MW. Marked by light yellow it is seen that 10 MW is expected to be reached somewhere between 2014 and 2019, that 100 MW is reached somewhere between 2016 and 2020 and that 1.000 MW can be expected to be reached before around 2030. Notice that the numbers presented in the table below assume that all cars are plugged in.

Table 33 – MW balancing effect assuming 3-phased 230 V 16 Amp socket

DK %		2012	2013	2014	2015	2016	2017	2018	2019	2020	2030	2040	2050
USA	Scenario 1 Cum.	-	-	-	0	1	1	6	15	29			
	Scenario 2 Cum.	0	0	0	3	8	14	32	59	96			
	Scenario 3 Cum.	0	0	0	3	8	14	41	87	155			
Linde	Low uptake	-	-	-	-	2	21	55	90	124	1.289		
	High uptake	-	3	27	70	114	181	272	406	580	3.923		
HyWays	Low penetration									28	827	4.210	12.919
	Medium penetration									331	3.516	11.717	24.904
	High penetration									911	7.003	17.754	26.734

[15] Appr. 2 mio. cars in DK/ appr. 700 mio. cars in the world * 1,3 mio. Prius'

F.3 Energy requirements & cost for transport scenarios

In this chapter the transport technology scenarios are presented. First the vehicle scenarios are presented, next the transport demands in Denmark are investigated and finally the fuel supply systems are presented. Both technical and economic data are presented.

Then the results for the transport scenarios representing 500.000 vehicles are presented in the energy systems defined earlier. Please note that the efficiencies and costs of HFCV and BEV vehicles are based on potential future efficiencies and costs, and requires that further development is conducted as well as mass production of the electrolysers and of the vehicles.

F.3.1 Vehicle scenarios

The energy system analyses of transport solutions assume the replacement of 500.000 conventional vehicles. Two main vehicle references are used in the analyses: a standard diesel vehicle (ICE diesel) and a standard petrol vehicle (ICE petrol). Both of these have been combined with bio fuels as a potential for renewable energy using ICE. The three main alternatives in the analyses here are: hydrogen fuel cell vehicle (HFCV), Hybrid HFCV, as well as battery electric vehicles (BEV), all of which can potentially assist the integration of large amounts of wind power. In the analyses the main input is a coherent transport dataset from the Danish Energy Authority[123], with minor adjustments in the BEV, HFCV, hybrid HFCV as defined earlier.

An estimate for the specifications and costs of the Hybrid HFCV has been constructed for the analyses. The Hybrid HFCV is configured as a plug-in vehicle and can be characterised as a battery electric vehicle with FC as the range extender. The battery electric range of the hybrid HFCV is defined as 60 km with the heater off. The hybrid HFCV used in the in the analysis here is an estimate of how a vehicle could be configured; hence the specifications this kind of vehicle have in the future are connected to considerable uncertainties.

All vehicles are assumed to be comparable standard size vehicles with the same specifications, except that the range for BEV is lower. The demands for different range length are elaborated below in connection to the transport demand. For current BEV the range used is 135 km and for future BEV 200 km range is used with the heater off. The HFCV and the hybrid HFCV have ranges of approx. 600 km. In comparison today's standard vehicles typical have ranges above 800 km.

The level of hybridisation in HFCV is dependent on the technical possibilities as well as the consumer demands for increased range. Based on earlier parts the hybrid HFCV is assumed to have a range of 60 km operated on batteries, which covers 73 per cent of the average annual transport demand. The rest is covered by the fuel cell. It is assumed that vehicles with these characteristics are available from 2020.

The electrolysers for the hydrogen production for transport has a capacity corresponding to 50 per cent operation time. This corresponds to 600 MW for the HFCV and 160 MW for the Hybrid HFCV. The capacity of the hydrogen storage is one average week, which is illustrated above. In reality it seems as if marginal higher plant utilization and smaller storages is a more economical solution, however this limits the possibility to use wind power. The total efficiency of electricity to hydrogen in the vehicle from high temperature electrolysers is 67 per cent after taking into account losses for compression and for storage and distribution. 7.5 per cent may be utilised in heating systems. For alkaline electrolysers the efficiency is 56 per cent also taking into account these losses. Here 30 per cent may be used for heating . The data for the electrolysers can be found in the appendices, as can the amount of excess heat, which is utilised in the analyses. For the HFCV 600 MW electrolysers are installed and 33 GWh storage. For the Hybrid HFCV 160 MW electrolysers are installed and 9 GWh storage. This corresponds to one average week.

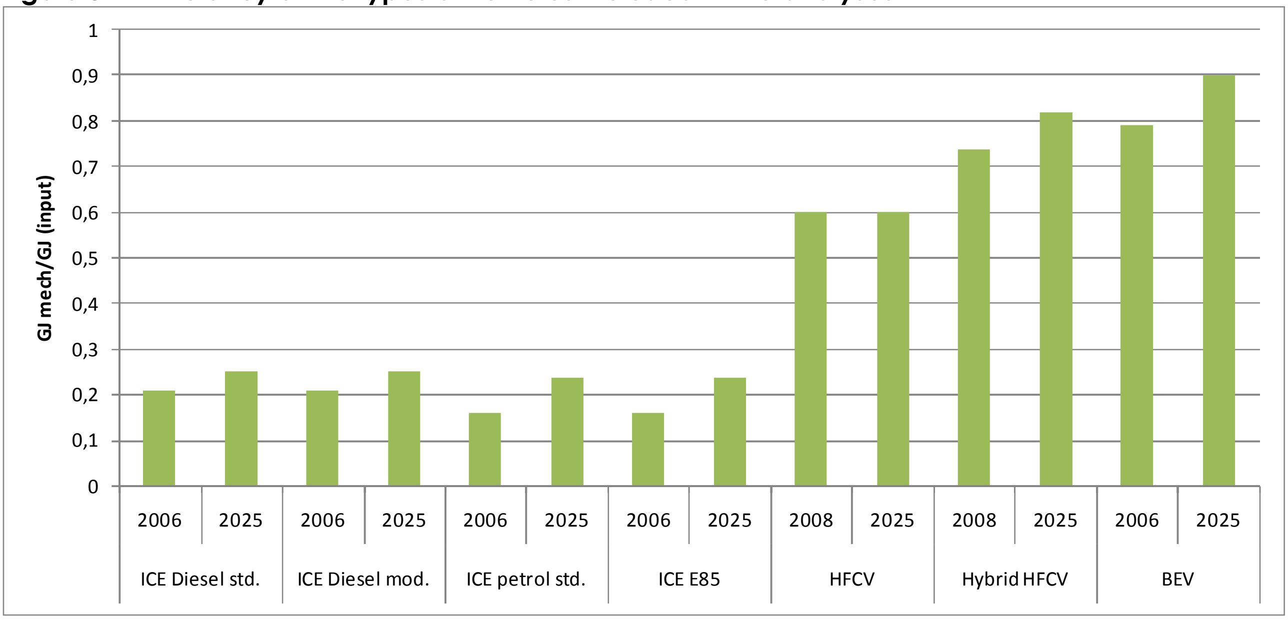
For diesel and petrol the transport infrastructure required is included in the sets of fuel handling prices used. The number of vehicles parked is rather high, even in rush hours. Here 20 per cent is used as the maximum number of vehicles parked, which is rather conservative and most likely underestimates the capacity connected. The amount of parked vehicles that are grid connected is assumed to be 70 per cent.
For bio-ethanol data from the Integrated Biomass Utilization System (IBUS) project is used. The data was used in the Danish Society of Engineers' (IDA) Energy Plan 2030.[124] Such a plant is assumed placed in the vicinity of a large existing extraction plant that uses biomass as supplementary fuel and can produce the necessary steam and heat with a high marginal efficiency. 42 DKK/GJ is added for distribution from the plant to the fuelling stations.[125]

For rapeseed oil an unrefined bio-oil product is assumed used in the vehicles. Pressed rapeseed oil is a simpler process as the refinement process can be avoided. A 96 per cent efficiency from rapeseed to bio-oil is used, production costs of 87 DKK/GJ bio-oil and 27 DKK/GJ in distribution costs is used[126], excluding electricity. The price fluctuates by 11,25 DKK from the base price of 87 DKK/GJ. The electricity used is approx. 1,5 per cent of the energy contents in the rapeseed oil, and is included in the analyses.

In the figure below the efficiency of the types of vehicles included in the analyses are illustrated. The lifetime of the vehicles is assumed to be 13 years. The BEV has the highest efficiency, while the ICE technologies have the lowest. The hybrid HFCV efficiency is dependent on the share of transport demand being met by the onboard battery. The hybrid HFCV efficiency is also dependent on the batteries being connected directly to the grid in order to avoid using the fuel cells in too many situations. The HFCV also has a battery installed. The battery is rather small but allows for the fuel cell to operate at optimal conditions in many situations. In the calculations conducted here hydrogen is used as the fuel, however methanol in HT-PEMFC is another potential configuration.

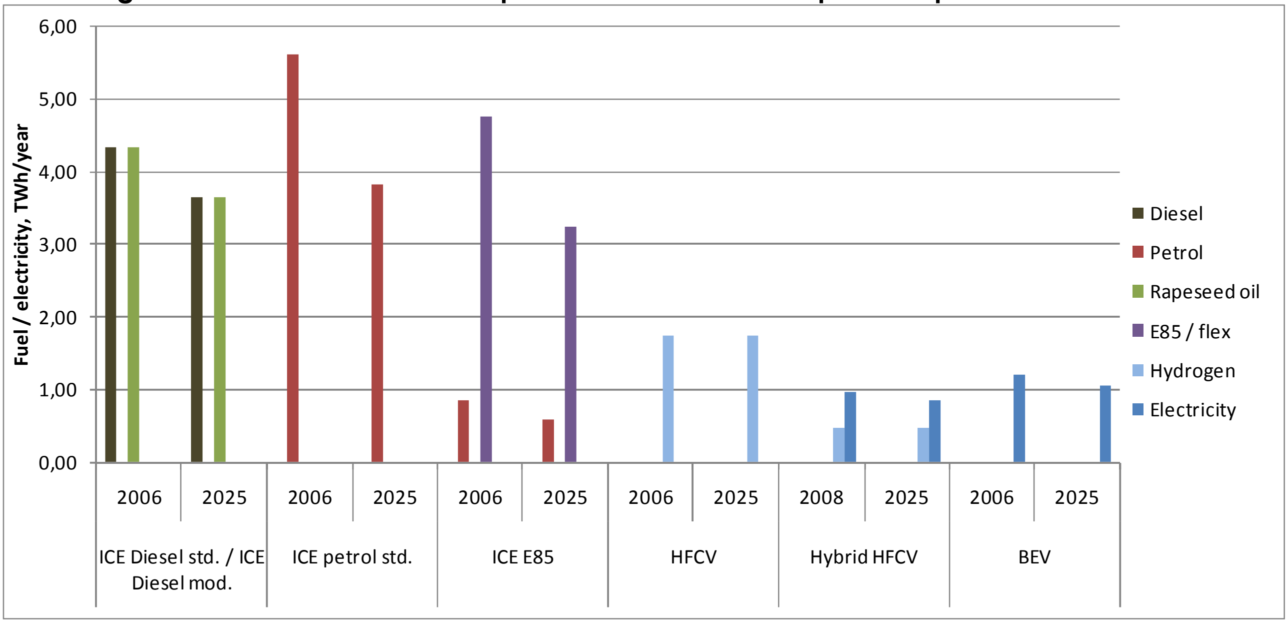
The efficiencies of the vehicles and the battery costs are included in sensitivity analyses.

Figure 32 – Efficiency of the types of vehicles included in the analyses



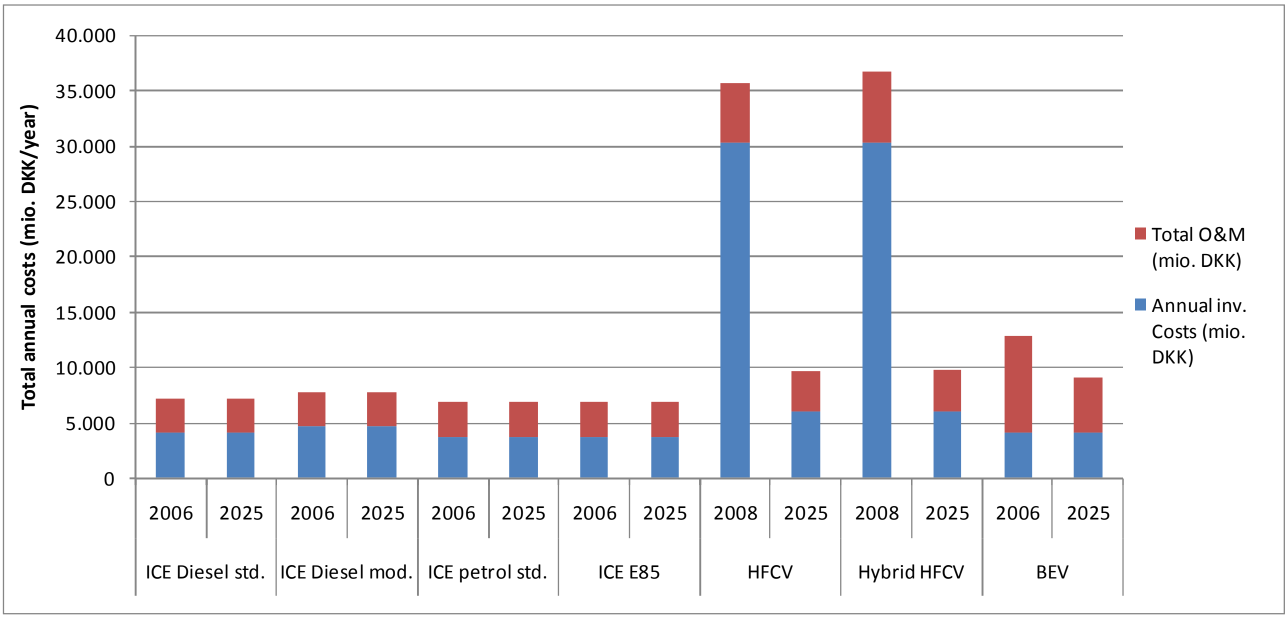
The fuel or electricity consumption as a result of using half a million different vehicles is presented in the figure below. The different types of vehicles require different fuels and different infrastructure. The hybrid HFCV needs to be able to be fuelled with both hydrogen and electricity, but may however require less hydrogen fuelling stations than the HFCV.

Figure 33 – Fuel or electricity consumption for 500.000 vehicles using different drive train technologies. E85 is a term used for 85 per cent ethanol and 15 per cent petrol.



The costs of both BEV, HFCV and plug-in HFCV are rather high in the short term, but in the longer term, the prices are expected to decrease. This is however dependent on establishment of large-scale production facilities. In the future, ICE technologies are still expected to have the lowest investment costs, while in the future the costs of HFCV and Hybrid HFCV are expected to be 25 to 40 per cent higher and BEV are expected to be 15 to 30 per cent higher. The modified ICE diesel can use less costly rapeseed oil instead of the more refined biodiesel also based on rapeseed oil.

Figure 34 – Total annual costs of 500.000 vehicles based on different drive train technologies, incl. inInvestment costs and fixoperation and maintenance cost (O&M)



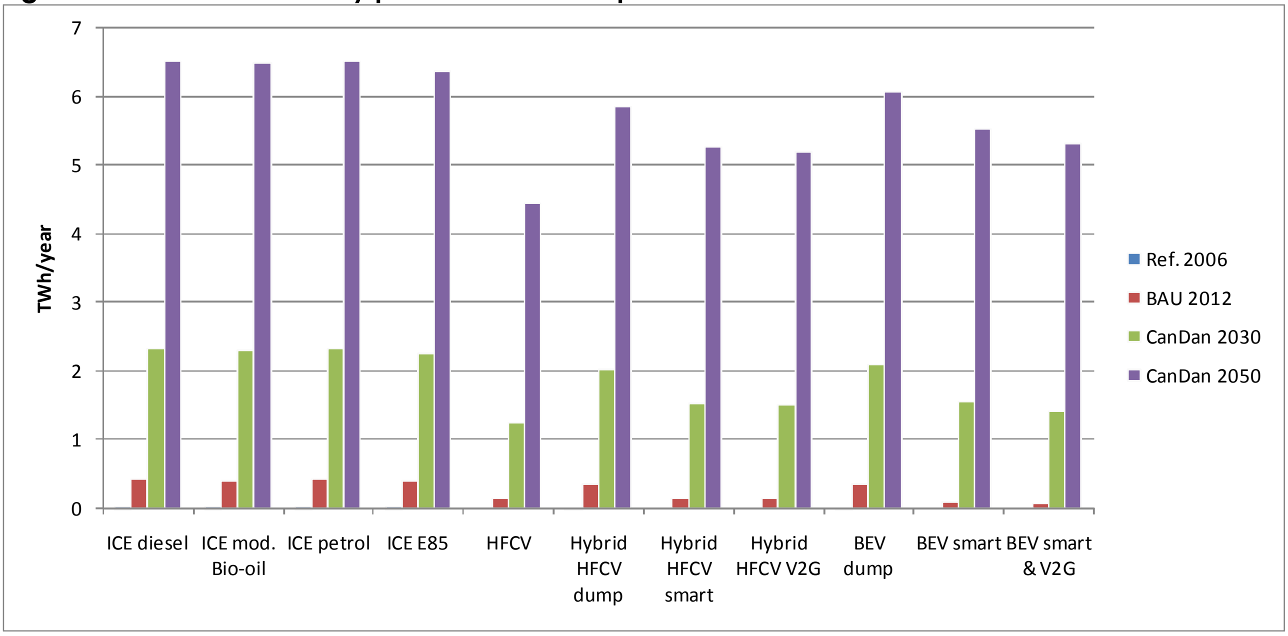
F.3.2 Fuel consumption, excess electricity and CO_2-emissions

In the technical energy system analyses the transport scenarios are analysed in closed energy systems, in which the interconnections with the surrounding countries are closed. In such analyses the consequences of technological changes can reveal the resulting fuel consumption and effects on the integration of renewable energy such as wind power. In the closed energy system analyses excess electricity production will occur with increasing amounts of wind power, if no other technologies are installed. The excess electricity production represents the least amount of TWh that Denmark is forced to export, or where other measured should be used. In analyses of electricity for the transport sector either for hydrogen in HFCV and hybrid HFCV or for BEV can be analysed regarding their ability to utilise wind power in such transport solutions.

The excess electricity production is very low in the present energy system however it increases in the future energy systems because no other integration technologies are installed in the energy systems constructed for the analyses here. As mentioned this represents an extreme situation which would not occur in reality, however in the analyses here, such energy systems can reveal the advantages and disadvantages of the different electricity consuming transport technologies.

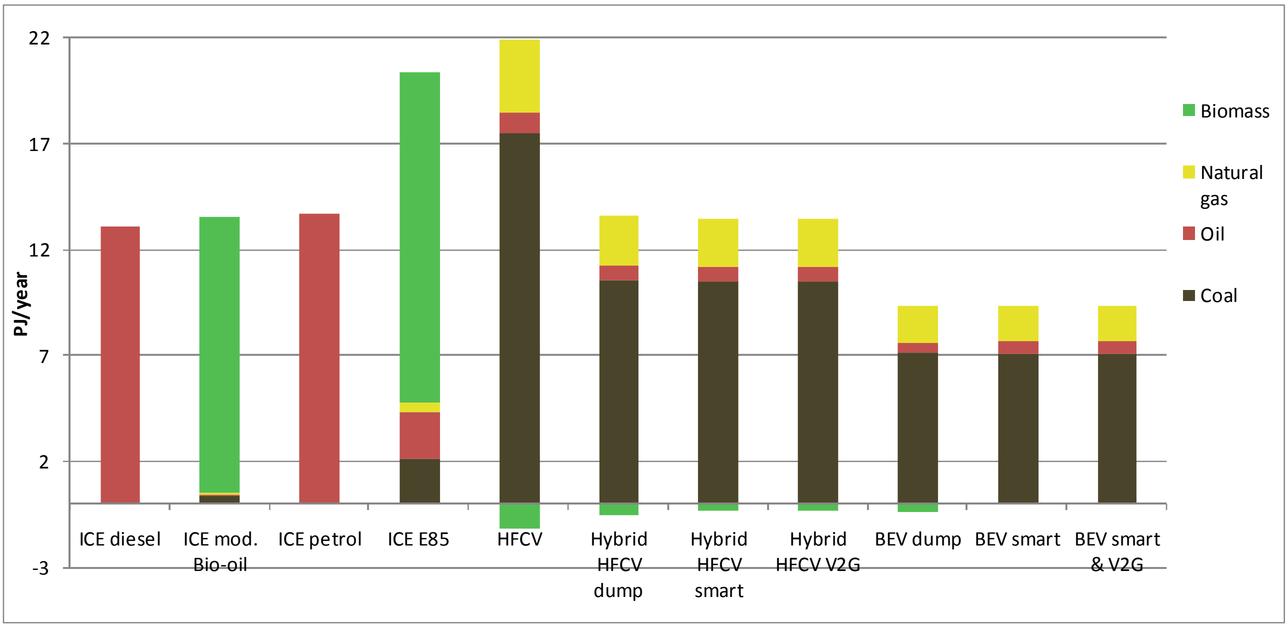
The 2012 energy system represent a system with the amount of wind power installed as a result of the expansion already planned. In Figure 35 the excess electricity production in the different energy systems is presented. In the BAU 2012 energy system the excess production is 0,4 TWh, in CanDan 2030 it is 2,31 TWh and in 2050 it is 6,5 TWh. The dump charge solutions represent technologies which place production at times where the vehicles are parked, while the smart charge solutions place electricity demand at times with excess production if possible. In the V2G solutions the technologies use the batteries installed to charge at times with excess production and replace production at PP. In 2012 the smart charge and V2G hybrid HFCV and BEV as well as the HFCV can almost eliminate the excess electricity production that can be expected. In the 2030 and 2050 energy system the HFCV has the best ability to reduce excess electricity production. The hydrogen production is placed at times with excess electricity production if possible. This is connected to the fact, that the demand for electricity is larger in the HFCV solutions than for other transport scenarios, hence it presents more opportunities to reduce excess production. The dump charge technologies does not present good solutions for reducing excess production, as these have electricity demands that only by chance reduces excess production. The smart charge and V2G technologies have similar abilities to reduce excess production. The V2G solutions are marginally better than the smart charge technologies.

Figure 35 – Excess electricity production of transport scenarios



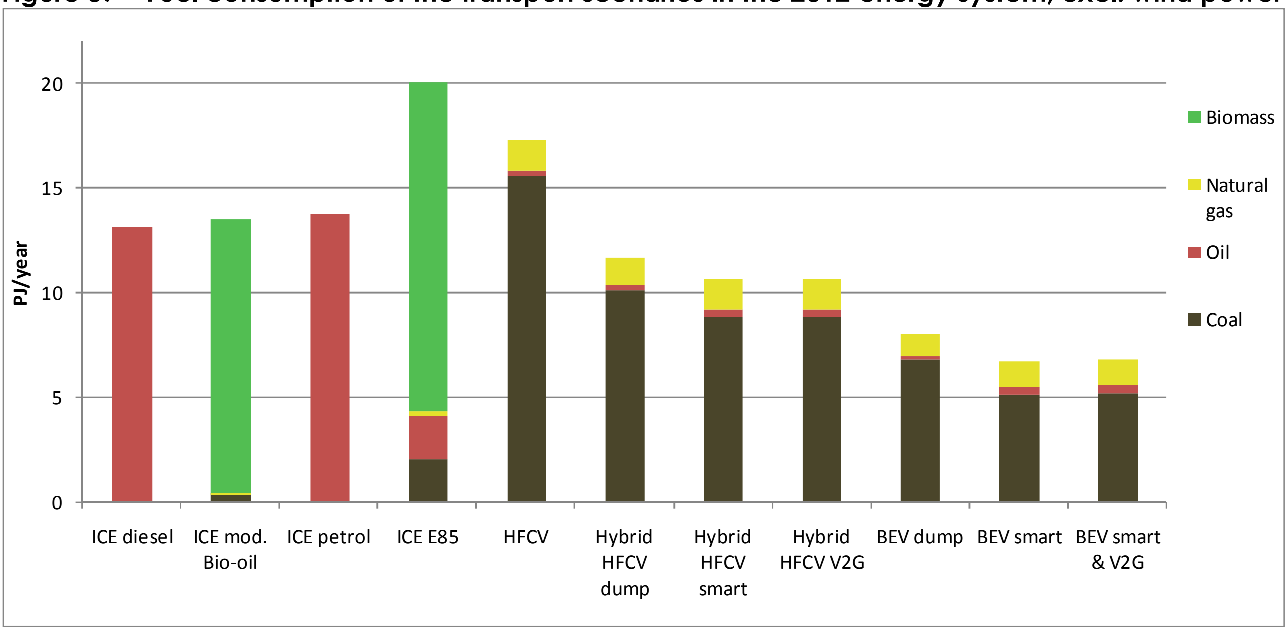
In Figure 36 and Figure 37 the fuel consumption of the technical energy system analyses of the transport technologies are presented for the current 2006 system and the future 2012 energy system. The fuel consumption for 500.000 vehicles is lowest for the BEV technologies, while the largest fuel consumption is connected to the 85 per cent bio ethanol solution and the HFCV. For the hybrid HFCV and the other ICE technologies the fuel consumption is at the same level. Hence in a situation with no excess renewable energy, the total efficiency of producing electricity for BEV is more efficient than the ICE technologies, while the gains in efficiency in hybrid HFCV is lost because of the electricity production for hydrogen. In the analyses of the 2006 energy system the marginal savings of biomass for some of the transport technologies reflects that CHP plants produces more electricity and can replace boiler heat production. While some of the increased electricity demands can be produced at CHP plants operating on natural gas or coal, PPs primarily fuelled by coal also produces electricity.

Figure 36 – Fuel consumption of transport scenarios in technical energy system analyses in the 2006 energy system, excl. wind power



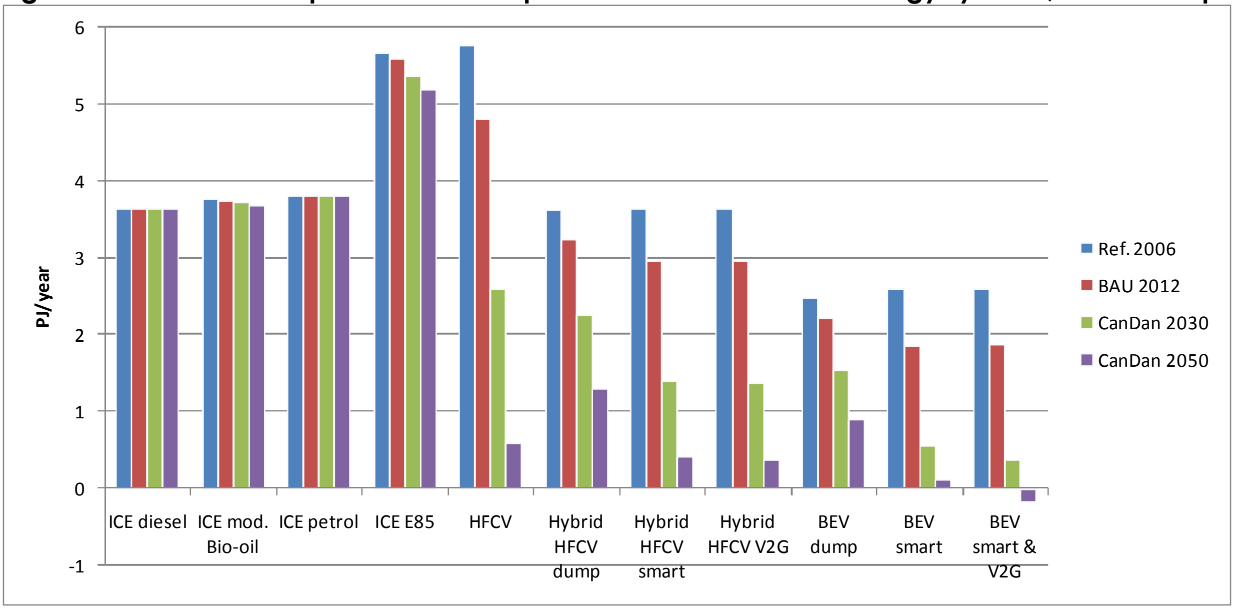
In the 2012 energy system 5,45 TWh wind power is added representing 32 per cent of the electricity demand. This increases the possibilities of meeting electricity demand for transport with wind power, and, as a result, the fuel consumption for these technologies is reduced. In this energy system the total fuel consumption of HFCV is lower than ICE E58. Also the fuel consumption of the Hybrid HFCV solutions is lower than the remaining ICE technologies. In the 2012 energy system the possibility for smart charge can decrease the fuel consumption, while the possibility to use the V2G technology does not decrease fuel consumption further.

Figure 37 – Fuel consumption of the transport scenarios in the 2012 energy system, excl. wind power



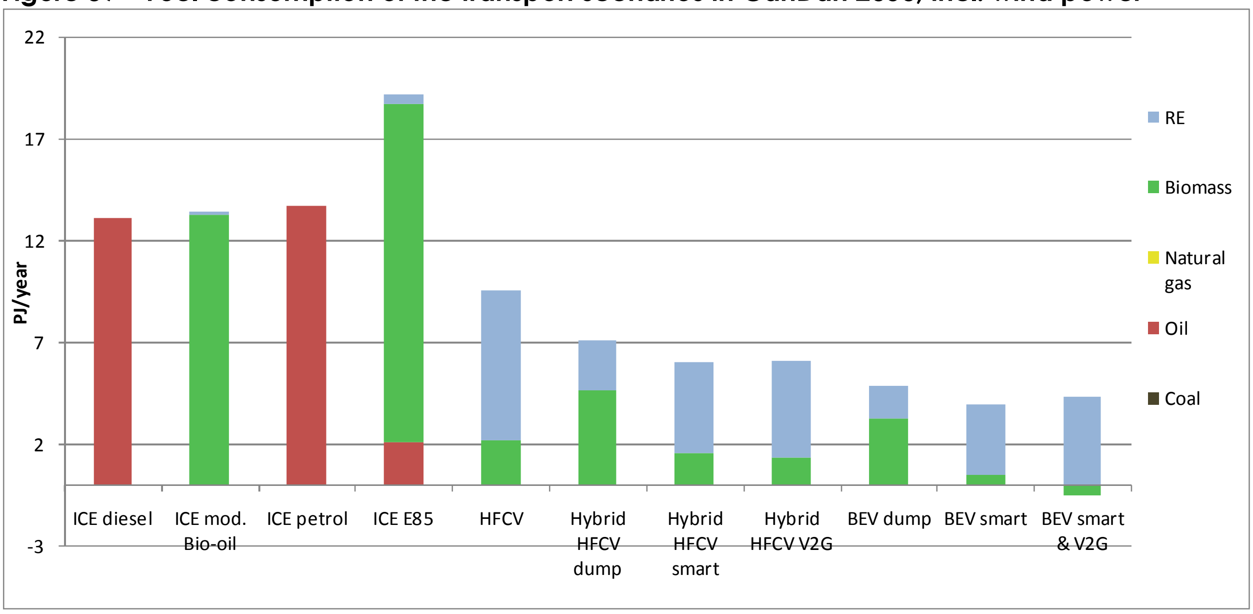
In the 2030 and 2050 energy systems the HFCV is able to use more and more of the wind power installed as the amount of excess electricity increases. In these energy systems the ability to use excess wind power becomes increasingly important. In Figure 38 the results of the all transport scenarios are presents in all energy systems. The smart charge and V2G BEV solutions have the lowest fuel consumption compared to the other technologies in all energy systems. The dump charge BEV has lower fuel consumption than other technologies in the 2006 and 2012 energy system. In the 2030 and 2050 energy systems however, the hybrid HFCV have lower fuel consumption than dump charge BEV. The HFCV has lower fuel consumption than ICE technologies in the 2030 energy system and in the 2050 energy system, the fuel consumption may become lower than dump charge BEV. This reflects the fact, that with a larger electricity consumption in HFCV than for other vehicle, hydrogen storage and plenty of excess wind power available enable the use of large amounts of wind power.

Figure 38 – Fuel consumption of the transport scenarios in the four energy systems, excl. wind power



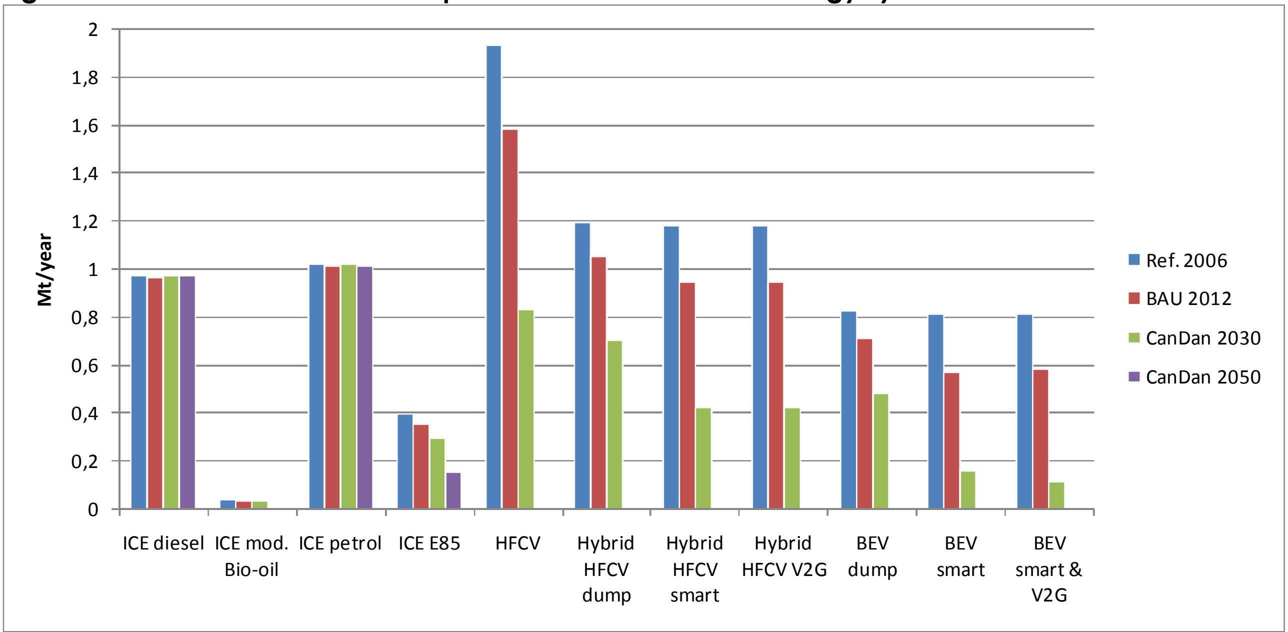
The fuel consumption and wind power consumption for the transport solutions in the CanDan 2050 energy system is illustrated in Figure 39. In this energy system, the BEV solution with smart charge and V2G provides the best option for reducing the overall fuel consumption and effectively utilise wind power. It may even result in a net replacement of fuels in CHP and PP.

Figure 39 – Fuel consumption of the transport scenarios in CanDan 2050, incl. wind power



The CO_2-emissions of the transport technologies is presented in Figure 40. The bio-oil and E85 scenarios present rather low CO_2-emissions in all energy systems analysed. The hydrogen production presents significant problems in the energy systems for today and for 2012, because the excess electricity production is rather low, and hence the electricity has to be produced partly at coal fired power plants. With more and more wind power, the CO_2-emissions become lower and lower for hydrogen production. The BEV scenarios have lower CO_2-emissions than the conventional technologies also in the current energy system. The CO_2-emissions of the BEV scenarios is lower than all the HFCV solutions.

Figure 40 – CO_2-emissions for transport scenarios in the four energy systems



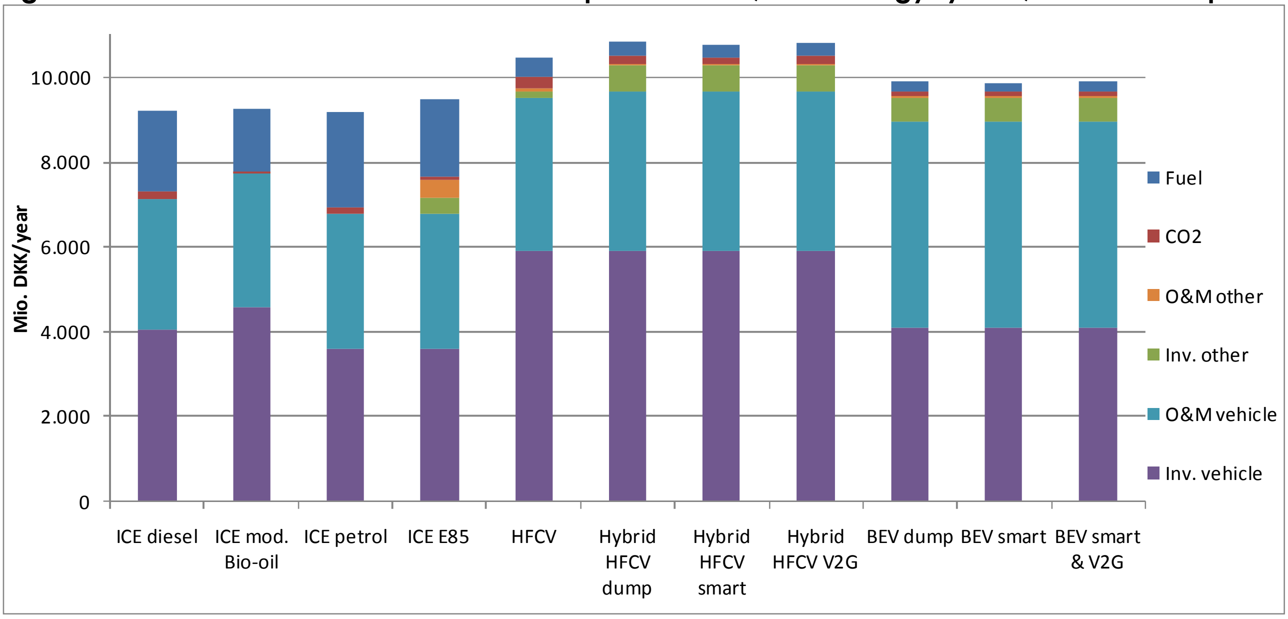
F.3.3 Socio-economic costs transport scenarios

In the calculations of the socio-economic costs of the different transport solutions the energy system analyses is still conducted for a closed energy system, however in these analyses the CHP plant, PP and boilers produce with the aim of having the lowest overall costs. Production is placed at plants with the lowest marginal costs. In these analyses the electricity demand for transport is placed at times with the lowest costs if possible, and for V2G solutions electricity is sold at times with a profit for V2G.

In Figure 41 the socio-economic costs of the transport scenarios is presented in the 2012 energy system. With medium fuel prices equivalent to 87$/bbl, including CO_2-costs, and technology and vehicle costs described above, the conventional ICE vehicles have the lowest costs. All the BEV technologies analysed have lower cost than the HFCV technologies. The total annual costs of BEVs are approx. 900 mio. DKK lower than Hybrid HFCV and approx. 500 mio. DKK lower than HFCV. Generally the investment costs are high for the BEV and HFCV transport scenarios, while the fuel costs are high for the ICE technologies.

The HFCV has marginally lower costs than the hybrid HFCV technologies analysed. This is due to the fact, that this is not a plug-in vehicle and thus does not require charging stations like the hybrid HFCV. In the analyses here the electrolysers and caverns for hydrogen storage are included as is the costs of compression for hydrogen vehicles. For ICE vehicles the distribution costs of fuels are included. The costs of the petrol stations as such (local storage, buildings etc.) is assumed the negligible for ICE and HFCV, and potential new pipelines for hydrogen distribution are not included.

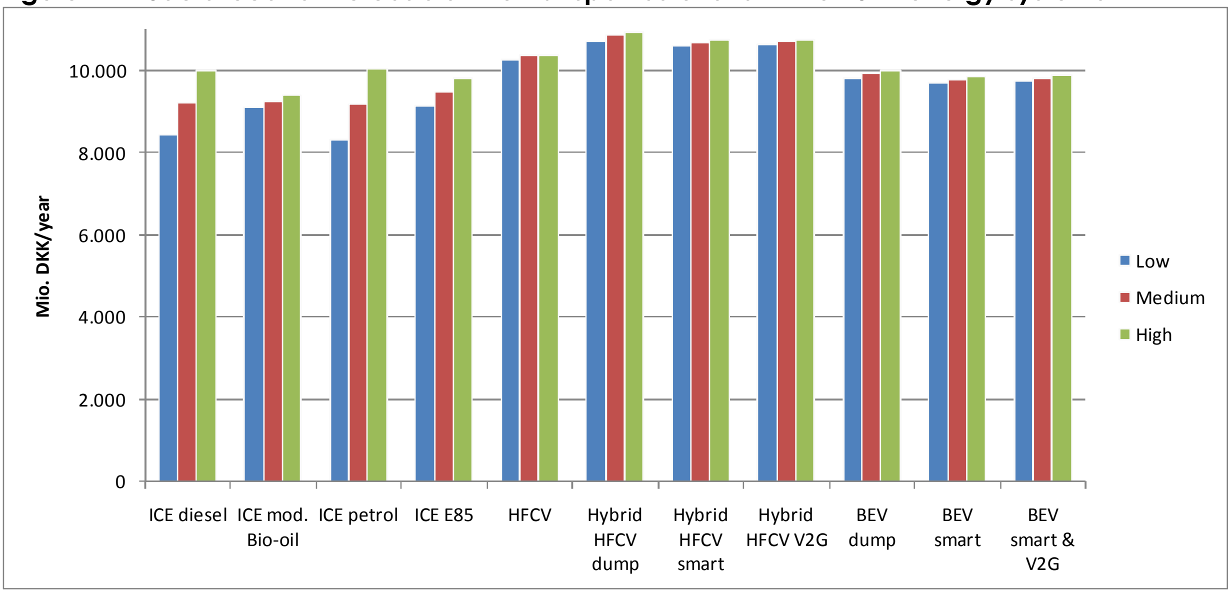
Figure 41 – Socio-economic costs of the transport solutions, 2012 energy system, medium fuel prices



In

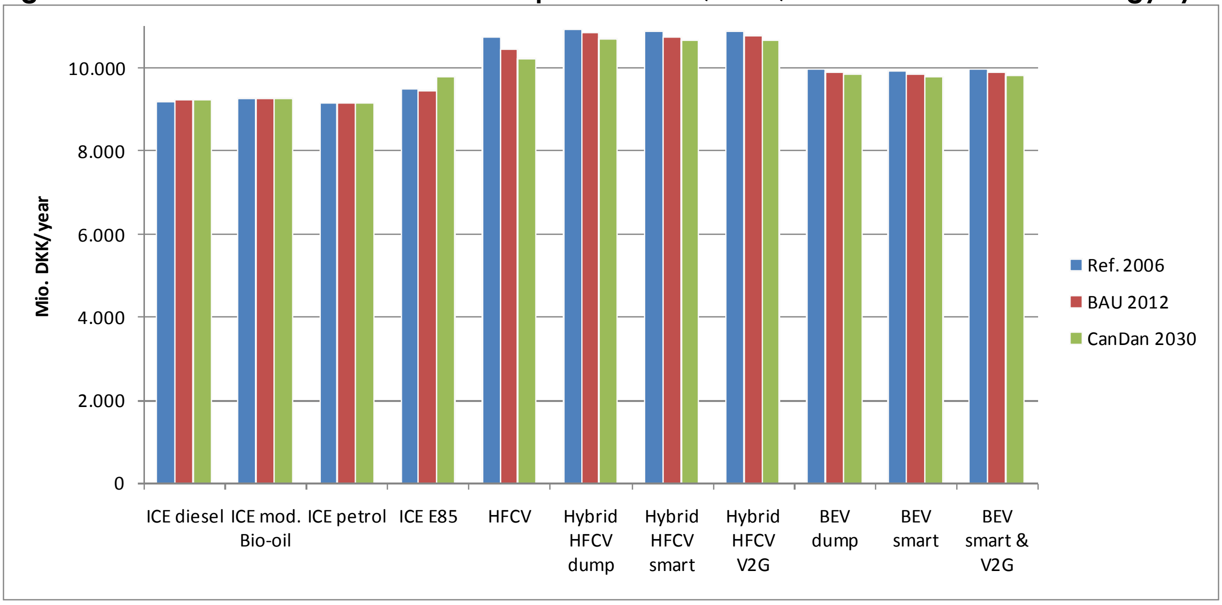
Figure **42** the socio-economic costs of the transport solutions in the 2012 energy systems with low, medium and high fuel prices equivalent to 47, 87 and 129$/bbl oil is illustrated. With low fuel prices the ICE diesel and petrol transport scenarios have the lowest total annual costs. With high fuel prices these vehicles have higher costs than the BEV scenarios. This reflects the situation where the conventional transport technologies have a high fuel consumption, which makes them vulnerable for fluctuating fuel prices.

Figure 42 – Socio-economic costs of the transport solutions in the 2012 energy systems



If we compare the costs of the different transport scenarios analysed in the remaining energy systems with medium fuel prices equivalent to 87$/bbl oil, the picture does not change significantly. The results are illustrated in Figure 43. Although the cost of fuels is reduced, because the HFCV and BEV technologies can utilise gradually more and more wind power, the ranking of the technologies does not change from an economic perspective. In the CanDan 2050 energy system, which is based on 100 per cent renewable energy, the ranking is also the same. The cost of fuels in such a system is however connected to considerable uncertainties.

Figure 43 – Socio-economic costs of transport solutions, 2006, 2012 & CanDan 2030 energy systems



For the V2G technology, both in the hybrid HFCV and BEV, the fuel consumption increases slightly, as the V2G vehicles attempts to minimise the costs, and may find solutions, that increase the fuel consumption, because it may store electricity at times with cheap electricity production from other plants than from wind turbines and because there are losses in the storage. As illustrated in the technical energy systems analyses of the fuel consumption though, the V2G technology can decrease the total fuel consumption.

The transport scenarios have also been analysed with low, medium and high fuel prices in all energy systems. The ranking of the technologies does not change from the results presented for the 2012 energy system.

In the 2050 energy system though the HFCV is able to minimize the fuel costs and hence have marginally lower costs than the ICE E85. However the BEV scenarios still have lower costs.

F.3.4 The socio-economic costs of hydrogen

In the analyses of the socio-economic costs presented above, the costs of wind turbines has not been included, as the aim of the analyses was to analyse the transport scenarios in different energy systems towards a 100 per cent renewable energy scenario. Here the lowest socio-economic costs of electricity for the electricity consuming technologies are presented, as are the lowest potential hydrogen costs. Please note, that the prices are connected to highly optimistic assumptions for the hydrogen infrastructures.

For such analyses the marginal costs of producing electricity is insufficient. For wind turbines the main costs are connected for the initial investment. For wind turbines the latest assumptions used by the Danish Energy Authority is used for turbines in 2020.[127] For on-shore turbines the investment and installation costs are 8 mio. DKK/MW, the O&M costs are 90 DKK/MWh, and the lifetime is 20 years. With 30 per cent full load hours the long term production socio-economic costs is 290 DKK/MWh. Off-shore turbines are more expensive and have total investment and installation costs of 14 mio. DKK/MW, the O&M costs are 110 DKK/MWh, and the lifetime is 25 years. With 40 per cent full load hours the long term production socio-economic costs is 332 DKK/MWh. These costs are rather low compared to the total long term costs of other technologies, except for coal with low fuel prices and no CO_2-costs. These long term electricity costs for wind power is used for identifying the lowest possible long term costs of hydrogen production.

Here the production cost of hydrogen for different purposes is identified. The maximum total efficiency from electricity to hydrogen in the vehicle is 67 per cent using high temperature electrolysers with inverters, storage in caverns and compression. Such losses results in 441 DKK/MWh hydrogen (14,7 DKK/kg hydrogen), including the capital costs of these technologies. If alkaline electrolysers are used, the costs are 526 DKK/MWh hydrogen (17,5 DKK/kg hydrogen). If we assume oil boilers can be replaced by the heat production from the electrolysers at medium fuel prices, the costs are reduced to 418 and 436 DKK/MWh respectively (13,9 or 14,5 DKK/kg respectively - or 116 and 117 DKK/GJ). To obtain these prices the following development has to be achieved technical and economically:

1) the costs of electrolysers are reduced and that the electrolysers are able to operate at times with low electricity prices (such as when wind power is being produced), i.e. have very goods regulation abilities
2) the storage facilities have very low costs and high efficiencies (such as caverns)
3) the storage periods are short (see description of caverns above)
4) the distribution of hydrogen from caverns have very low costs and high efficiencies
5) the compression of hydrogen to vehicles have low cost and high efficiencies
6) the excess heat can be utilised

With small scale liquid gas storage, the price increase to at least approx. 45 DKK/kg, and then the distribution costs have to be added. Today the costs are approx. 100 DKK/kg at approx. 400 bar.

Storage of hydrogen in caverns may not be possible. If a large-scale liquid gas tank is used with losses of 30 per cent, the costs of hydrogen can be expected to be between 570 and 618 DKK/MWh or approx. 21 DKK/kg. For other analyses such prices on hydrogen should be used.

In the energy system analyses the marginal production costs of hydrogen can be identified. In the 2006 energy system, such costs are 31 DKK/kg. In the 2012 and 2030 energy systems the costs approx. 24 DKK/kg, incl. Long term investment costs in CCGT. In the 2050 energy system the amounts of excess electricity are large enough to cover most of the production at electrolysers, and thus with the assumptions and requirements described above the price of hydrogen is 14 DKK/kg. However this situation is not possible to achieve, as other technologies would be installed, in order to reduce the large amounts of excess electricity production before such a situation is possible. The electrolysers would have to compete with such technologies, e.g. replacing oil, natural gas or biomass in boiler directly with electric boilers or geothermal heat pumps. Hence the long term production price are likely to be between 31 DKK/kg and 24 DKK/kg until other options are used for the integrating renewable energy. Also if the wind turbines sell electricity at low prices over a long period, the expansion with new turbines will most likely be less. Fur further analysis's near term prices of 80 DKK/kg hydrogen and a long term price of 24 – 31 DKK/kg hydrogen is assumed. In the business analysis conducted later in this report the prices refer to high, low and medium prices respectively.

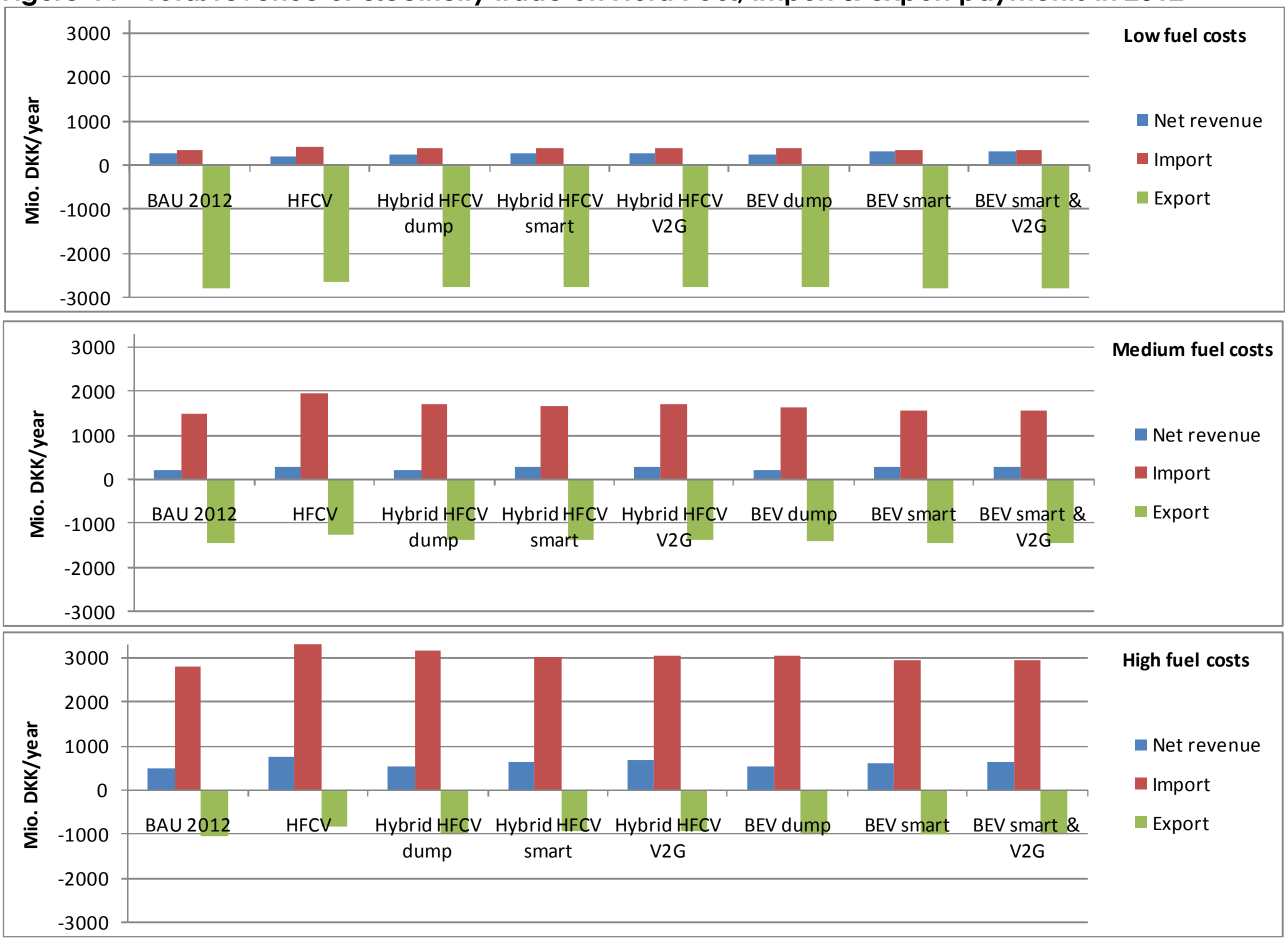
F.3.5 Market exchange analyses

In the market exchange analyses the transport solutions are analysed in open energy systems, in which the interconnections with the surrounding countries are used for trading electricity. In the analyses of the Danish energy systems conducted here, the electricity trade with Norway and Sweden on the Nordic electricity market (Nord Pool) is analysed for the transport solutions. In such analyses electricity is sold when prices are high and bought when prices are low.

In Figure 44 the net revenue of electricity trade is illustrated for the 2012 energy system without transport scenarios and with the transport scenarios. The net earnings illustrated are the differences between the socio-economic costs presented in Figure 43 in a closed system and the net revenue of electricity exchange. E.g. HFCV the net revenue is presented as the difference between the socio-economic costs presented for HFCV in the closed system in Figure 43 compared to a situation with electricity exchange.

For the 2012 energy system the net revenue is 263, 204 and 500 mio. DKK/year for low, medium and high fuel costs respectively. For the low fuel prices increases the export, while the import is increased significantly with the high fuel prices.

Figure 44 – Total revenue of electricity trade on Nord Pool, import & export payments in 2012



The question is what effects the different HFCV and BEV transport scenarios have on the ability to profit from electricity trade. The electrolysers and hydrogen storage increases the net revenue electricity trade for HFCV with high fuel costs, as import is cheaper than domestic production, and hence domestic fuel consumption can be lowered. In the situation with low fuel prices the situation is the opposite. Here the electricity demand of HFCV decreases the opportunities to export electricity produced with low fuel costs. The smart charge and the V2G Hybrid HFCV and BEV scenarios results in improved net earnings compared to the 2012 energy system without transport with low, medium and high fuel prices. These transport scenarios have lower electricity consumption, and thus have better opportunities to place demand at times with low cost electricity. The Hybrid HFCV V2G and BEV V2G scenarios have marginally higher net revenues than the smart charge scenarios.

In the 2006 energy system the amount of wind power is lower, and in more or less all situations the transport scenarios can profit from electricity trade. In the electricity market exchange analyses of the CanDan 2030 and 2050 energy systems the transport scenarios with electricity demands are generally lowers the ability to have net revenues. The results reveal that the higher the electricity demand and the less flexible demand, the lower the ability to profit from electricity exchange. However the V2G transport scenarios are still better than the other scenarios. This is connected to the fact, that the increases in efficiency of domestic electricity production at PP and CHP plants, lowers the production price, and hence in the CanDan 2030 and 2050 energy system, an extra electricity consumption decreases the earnings from export.

In Figure 45 the fuel consumption in the 2012 energy system is illustrated as well as the imported electricity consumed. The main difference is that the HFCV has a rather large hydrogen storage, which can be used to import electricity at times with low electricity price on the Nord Pool market, and replace domestic production. Mainly at times where coal fired power plants would otherwise be producing. The lower total fuel consumption for HFCV is hence connected to the fact that the losses in the production of electricity from the imported electricity is not illustrated in Figure 45.

Figure 45 – Fuel consumption & net electricity import in the transport scenarios, 2012 energy system

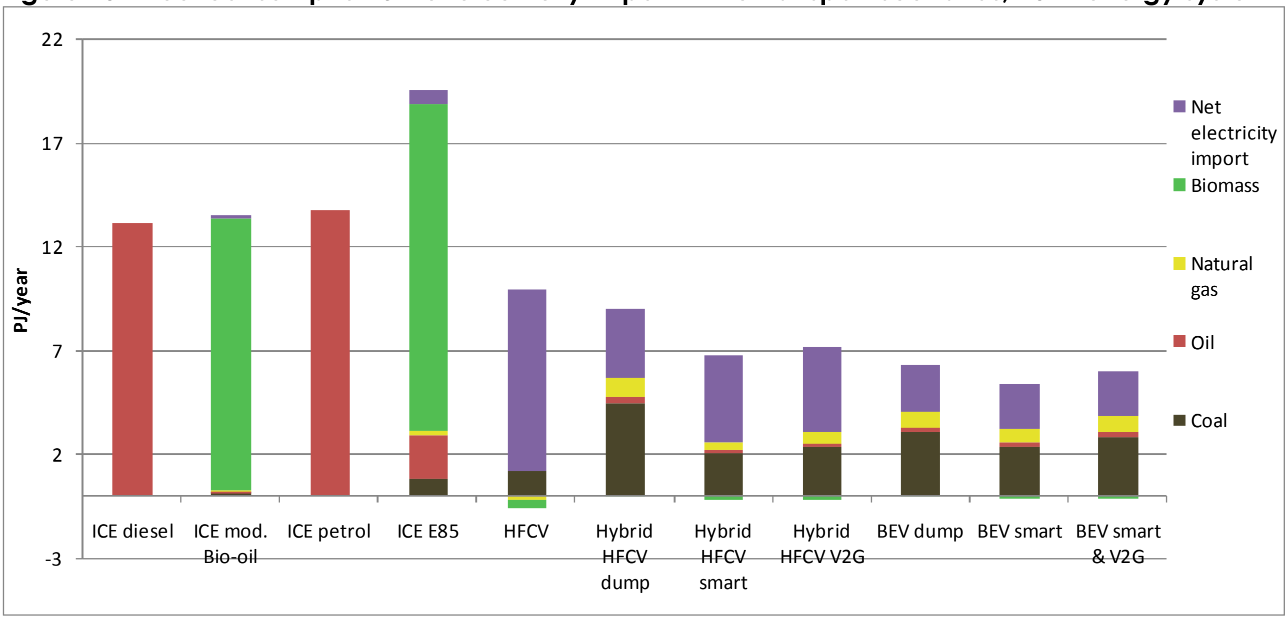
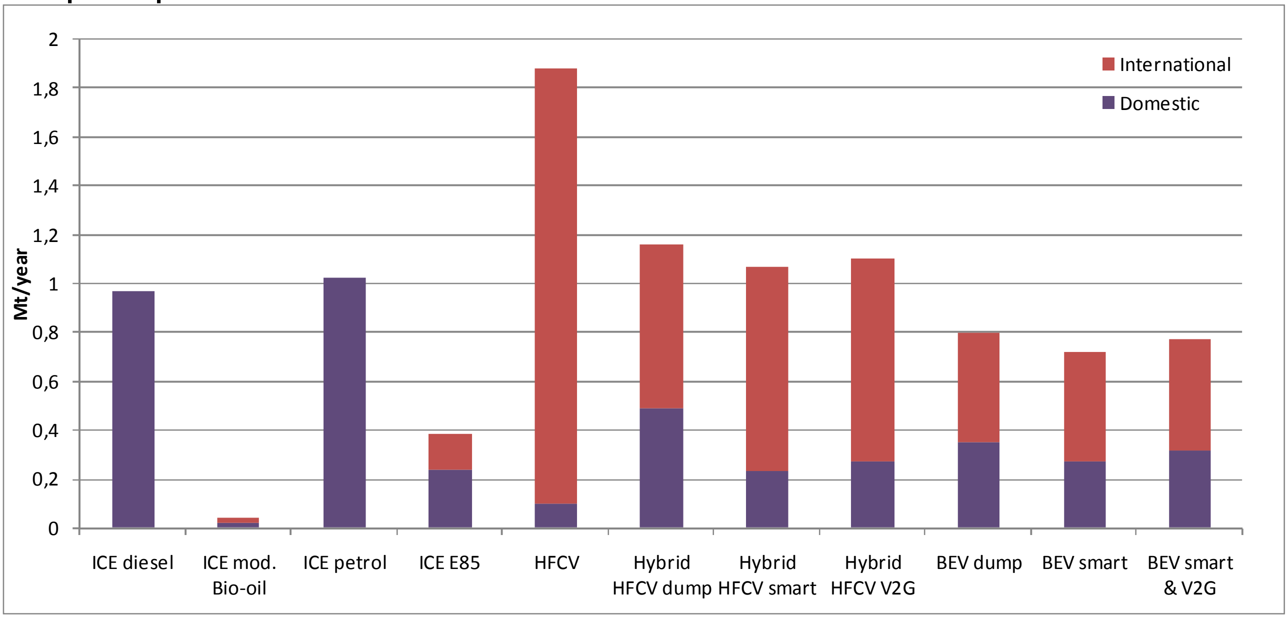


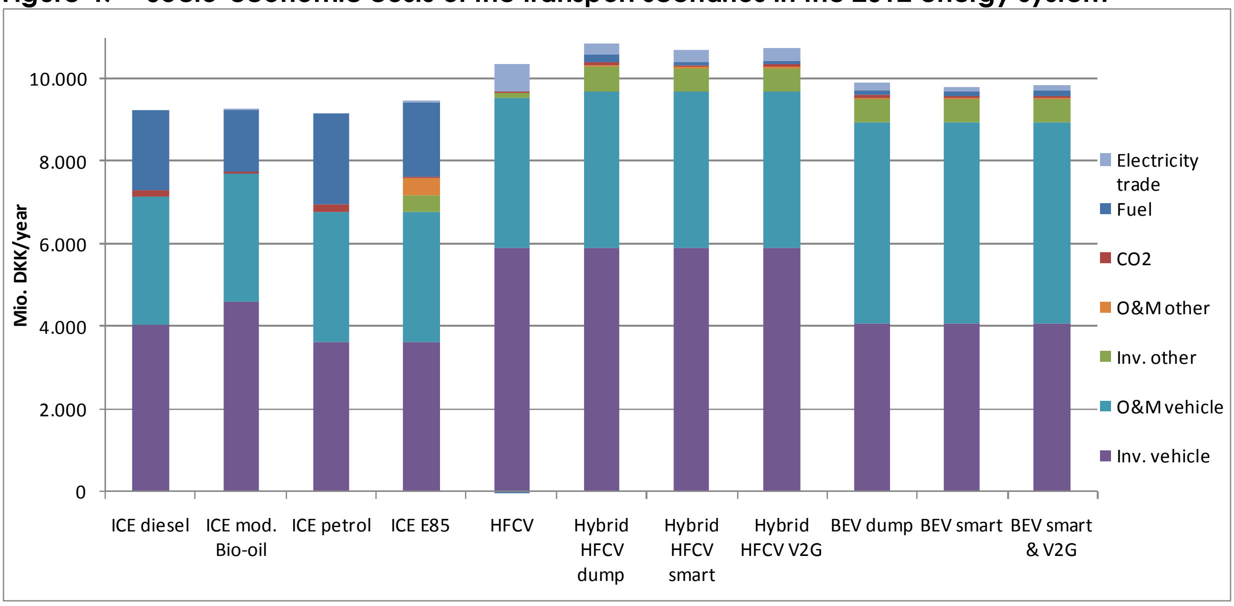
Figure 46 – CO_2-emissions domestically and from electricity imported in the 2012 energy system. The imported electricity is assumed to have CO2-emissions equal to the production at central coal fired power plants



This result is also reflected in the domestic CO_2-emissions as these become rather low for HFCV. However the CO_2-emissions from electricity production in other countries may also be connected with CO_2-emissions. The results are illustrated in Figure 46.

In Figure 47 the socio-economic costs is illustrated for the market exchange analyses of the transport scenarios in the 2012 energy system. Again the ranking of the scenarios does not change, although payments for domestic fuel to payments for electricity import. The socio-economic results for the transport scenarios in the other energy systems are similar to the results presented for the 2012 energy system, also with low and high fuel costs.

Figure 47 – Socio-economic costs of the transport scenarios in the 2012 energy system



F.3.6 Sensitivity analyses

In the sensitivity analyses some key assumptions in the transport scenarios are addressed.
The main sensitivity analyses are conducted for the HFCV and the BEV, as the effects of such changes will partly show the effects on the Hybrid HFCV.

For HFCV the capacity of hydrogen storage has been doubled, such an effort can reduce the total costs by approx. 10 mio. DKK/year. If the electrolyser size is also doubled the total socio-economic savings are reduced by approx. 70 mio. DKK/year in the technical energy system analyses of the CanDan 2030 energy system. In open and closed market economic energy system analyses the increased investment cost does not enable enough fuel savings to enable a net saving. Such changes do not change the overall ranking.

The HFCV have also been analysed in a situation with large liquid tank gas storages. Here the losses are larger, and the costs are higher. Such analyses reveal, that the costs of the HFCV alternative increases by 330 to 430 mio. DKK/year depending on the optimisation strategy and the energy system in which the transport scenario is analysed.

If the HFCV are analysed in combination with alkaline electrolysers, the significance of the heat production from electrolysers becomes important. These have lower electricity to hydrogen efficiency, but higher heat production. The costs may increase up to 80 mio. DKK/year. In some situations there may be small marginal savings, however, this does not change the overall results.

If the efficiencies of the HFCV are reduced from 60 to 50 per cent, and the electrolysers' capacity and the hydrogen storage are increased accordingly, the costs increase by between 150 and 250 mio. DKK/year depending on the optimisation strategy in the energy system analyses and the energy system.

If the BEV efficiency is reduced from 90 to 79 per cent, which is possible today, the costs would increase by 30 to 70 mio. DKK/year depending on the optimisation strategy in the energy system analyses and the energy system.

Modelling shows, that the range and efficiency of BEV may be 10 to 30 per cent lower, if heating or cooling is required is required.[128] This may be lower with better heat pumps or with better insulation. Assuming that the efficiency of BEV is decreased to as low as 60 per cent in e.g. some winter months because of the heating of the cabin, the total annual costs are increased by 180-250 mio. DKK/year in the 2006 energy system and 2012 energy system. In the 2030 energy system, the costs are between 120 and 174 mio. DKK/year. Even if the low efficiency is the case the entire year, the overall results does not change, however this will hardly be the case. The heating system will also have an effect on the efficiency and range of the Hybrid HFCV, because the battery covers most of the trips travelled.

If the total efficiency of the Hybrid HFCV is reduced from 82 per cent to 71 per cent reflecting by 79 per cent efficiency of BEV and 50 per cent of HFCV presented above, then the costs would increase by 40 to 100 mio. DKK/year depending on the optimisation strategy in the energy system analyses and the energy system.

The market exchange energy system analyses have been conducted in a situation with low electricity prices representing a wet year in the Nordic energy system (245 DKK/MWh) and in a dry year (658 DKK/year). Such analyses reveal that the HFCV are affected the most, the hybrid HFCV are affected second most and the BEV transport scenarios are affected the least. For the wet year, the HFCV costs are reduced by 160 mio. DKK/year, for the hybrid HFCV by 70 mio. DKK/year and for BEV by 45 mio. DKK/year. The opposite is more or less the case, when the situation is a dry year. The overall ranking does not change as a result of this. The effects of doubling the capacity of the interconnectors have been analysed for all system and technologies, and does not introduce any changes in the results.

If we increase the costs of batteries to 500 USD/KWh from 250 USD/KWh, the costs of BEV is increased by 1.707 mio. DKK/year, 605 mio. DKK/year for the hybrid HFCV and for the HFCV by 465 mio. DKK/year. Such large price difference would make the hybrid HFCV costs and the BEV costs balance, and would make the HFCV transport scenario have 700-800 mio. DKK/year in lower costs. If the lifetime of the batteries are reduced to 6 years, the Hybrid HFCV become marginally better than the battery electric vehicles.

The sensitivity analyses presented above have the largest effects on the CO_2-emissions in the situations where the losses in the hydrogen scenarios are reduced. If we change the interest rate to 6 per cent the overall ranking does not change.

F.3.7 Conclusion on transport scenarios

The vehicles using hydrogen are generally better at using excess electricity, i.e. to integrate fluctuating renewable energy than the battery electric vehicles. Already in 2012 the battery electric vehicles, which have the ability to charge at the right times, as well as hydrogen based vehicles may remove the excess electricity consumption. Although the hydrogen production at electrolysers may be able to remove excess electricity production, the efficiency is rather low. The battery electric vehicles have the lowest fuel consumption, already in the present energy system. The CO_2-emissions are also the lowest for the battery electric vehicles in the current and future energy systems.

For both the battery electric vehicles as well as the plug-in hybrid battery-hydrogen fuel cell vehicles it is important that the electricity demand is flexible. In the dump charge situation the potential to reduce the fuel consumption, CO_2-emissions and to integrate fluctuating renewable energy is improved with the ability to charge at times with wind power. This becomes increasingly important with more wind power, and can already be identified in 2012.

The energy system analyses conducted here represents systems with plenty of excess wind power. The results presented above are also true for the 2030 energy system with 50 per cent wind power and 100 per cent renewable energy system for 2050. In the future however, it is likely that both electrolysers and battery electric vehicles will have to compete with other technologies. In this situation the solutions with the most efficient uses of electricity is best of.

The socio-economic results reveal that the battery electric vehicles have lower costs than all the configurations of hydrogen fuel cells vehicles, also in hybrid solutions. This is the case in all the energy systems analysed towards 100 per cent renewable energy systems as well as for low, medium and high fuel prices. Thus the battery electric vehicles are less vulnerable to fluctuating energy prices. This is also the case when including electricity use for the heating systems in the battery electric vehicles.

With long term fuel costs between 87 and 129 $/bbl, as recommended by the IEA and the Danish Energy Authority, the socio-economic costs of battery electric vehicles are lower than for conventional ICE powered vehicles.

Please note that no externalities have been included in the socio-economic costs other than indirectly by the CO_2-trading scheme. If such costs had been included the highest costs would be connected to the transport scenarios with the highest use of fuels, especially fossil fuels. Such costs does not change that the battery electric vehicles have lower socio-economic costs than HFCV. In the 100 per cent renewable energy system the lowest fuel demand is for the battery electric vehicles.

The battery electric vehicles represents the most promising solution for integrating renewable energy based on the analyses presented here. These vehicles also represent an efficient strategy for local consumption of renewable energy, which can reduce the strain on the overall system stability and the demand for transmission of electricity.

The biomass based solutions included in the analyses represents low cost solutions comparable to conventional technologies, however the fuel consumption in these transport scenarios are rather high, and such biomass can be used to replace fuel in the electricity and heat production for e.g. hydrogen or battery electric vehicles.

The analyses presented here are based on the fact that the vehicles have the same size, however the range of battery electric vehicles is 200 km, which can cover 98 per cent of the total Danish transport demand, considering the driving ranges. Even with a range of 100 km, such vehicles can cover 85 per cent of the transport demand.

The results regarding fuel consumption, integration of fluctuating renewable energy sources and the CO_2-emissions are rather robust. For the socio-economic results the following issues areas should be noted:

The results of the hydrogen vehicles are primarily dependent on:

- the flexibility of electrolysers for producing hydrogen at times with wind power
- very low costs and highly efficient hydrogen storage and distribution
- the development of efficient fuel cell systems for vehicles

The results of the battery vehicles are primarily dependent on:

- Lower costs of batteries
- Longer life expectance of batteries

In the first phases of the implementation of battery electric vehicles, a solution may be to introduce smaller vehicle with shorter ranges, until the batteries are improved. The flexibility of electrolysers are uncertain and represents a problem for integrating fluctuation renewable energy, also in future high temperature electrolysers based on solid oxide cells. The fuel consumptions and CO_2-emissions are larger than for current vehicles until we have more than 50 per cent wind power in the hydrogen vehicle transport scenarios. Also, if hydrogen is not produced according to the wind power production at this time, the fuel consumption and CO_2-emissions may remain larger than for the current vehicles.

F.3.8 Conclusion on possibilities for hybridization

The electric grid can in this report be hybridized by using three technologies, batteries, electrolysers and fuel cells. In the table below these three technologies are seen in the column to the left. Please note that other technologies such as heat pumps can also play an important role. These, however are not considered here.

When hybridizing the electric grid down and up the most economical solution in the future is, due to lower costs, longer life expectancy and high energy efficiency, batteries.

If this is not enough to hybridize the electricity grid at a specific time in the future, future solid oxide electrolysers are the second best option to hybridize the electric grid of the options analyzed (order 2 electrolysers).

The third possibility, fuel cells in vehicles to hybridize the electric grid is associated with a long energy-chain and a low overall efficiency when compared to batteries, and hence this is the last option to be used.

In the table below "A" and "B" refers to intern order for batteries, electrolysers and fuel cells to hybridize the electric grid. Batteries and fuel cells are e.g. better at providing down regulating than up regulating, whereas electrolysers are equally good at providing down- and up-regulation assuming that they are running at partial load – e.g. at 70 % load.

It is furthermore seen what happens when each of the six hybridization modes are used.

For batteries providing down regulation the State of Charge (SOC) e.g. increases. Since energy is running from grid to vehicle this is termed Grid-To-Vehicle (GTV). This can happen several times a day. Using batteries for down-regulation can be used for both power regulation and as energy regulation. The power regulation will be used to regulate the power and the frequency (50 Hz) in the grid. The energy regulation will be in the form of charging the vehicle. This will often happen during nighttimes using electricity from wind turbines.

The longest energy chain possible in the table below is using electricity from fuel cells to hybridize the grid. Since there exists more efficient electricity producing technologies this option should in general only be used in extraordinary situations. Such situations could be power outrages due to ising, grid breakdowns, failure of interconnections to e.g. Norway, power plant failure etc.

Table 34 – Overview of the energy and power balancing possibilities

Order	**Down-reg.** (less electricity in grid)	**Up-reg.** (more electricity in grid)
1) Batteries	* Technology: Batteries * What happens: battery SOC ↑ (GTV) * Order: 1A * How often: Several times daily * Power and energy	* Technology: Batteries * What happens: battery SOC ↓ (VTG) * Order: 1B * How often: Several times daily * Power and energy
2) Electrolysers	* Technology: Electrolyser * What happens: H2 Production ↑ + heat ↑ * Order: 2A * How often: Daily (most nights) * Energy (and power)	* Technology: Electrolyser * What happens: H2 Production ↓ + heat ↓ * Order: 2B * How often: Daily (most days during peak hours) * Energy (and power)
3) Fuel cells	* Technology: Fuel cells * What happens: H2 refuelling↑, hydrogen use for driving ↑, (GTV) * Order: 3A * How often: Now and then * Energy	* Technology: Fuel cells * What happens: Electricity from FC to grid (VTG) * Order: 3B * How often: Few times each year (storms, grid breakdowns etc.) * Energy

F.4 Business analysis of balancing potential

Few international analyses' exists to the knowledge of the authors regarding fuel cells that provide energy to the electric grid. It has been judged that the best methodology is the one that Kempton from University of Delaware, US have developed throughout a decade or more of research into V2G. The methodology in Kemptons article "Vehicle-to-grid power fundamentals: calculating capacity and net revenue" from 2004 is used.[129] It is suggested that future V2G analyses are based upon this methodology, thereby providing a common platform on which different assumptions regarding each factor can be changed, analysed and discussed. Primary reserves, regulation and spinning reserves will be analysed here, whereas peak power and base load power are not analysed.

The terms "Primary reserves" and "Regulation" which is used in this report is by Kempton[130] termed "Regulation". The higher degree of fluctuating power the bigger is the market for, and thereby the bigger is the need to have, separately terms for frequency and voltage levels. The fact that there are separately terms in the Danish electricity grid-sector might be an indicator of the higher penetration rate of renewable energy in the Danish electricity market compared to the North-east-American market that Kempton normally analyze. In the table below the differences between the terms used so far in this report and the terms used by Kempton is seen.

Table 35 – Danish and Kempton terms for different electricity markets

Danish terms	Kempton term
Primary reserves	Regulation
Regulation	Regulation
Spinning reserves	Spinning reserves
? (Not described)	Peak power
? (Not described)	Baseload

The results presented are excluding taxes, VAT etc., but including transport and distribution. A discount rate of 10 % is used. The difference between the macro and the micro discount rate of 7 % (3 versus 10 %) is due the time horizon that the public versus private consumers and/or private entities use.

Primary reserves and regulation is controlled automatically, by a direct connection from the grid operator. In combination they are called for approximately 400 times per day in the US. The Danish numbers haven't been found why the US numbers are used. The actual energy dispatched for regulation is some fraction of the total power available and contracted for. The ratio is important to the economics of V2G, of which reason the "dispatch to contract" ratio is defined. The ratio is defined as:

$$R_{d\text{-}c} = E_{disp}/P_{contr}\,t_{contr} \qquad (1)$$

Where $R_{d\text{-}c}$ is the dispatch to contract ratio. (dimensionless), E_{disp} the total energy dispatched over the contract period (MWh), P_{contr} the contracted capacity (MW), and t_{contr} is the duration of the contract (hrs). $R_{d\text{-}c}$ should be calculated separately for regulation up (+) and down (-) for both primary reserves and regulation. It hasn't been possibly to find the separately nor combined numbers for $R_{d\text{-}c}$. Neither has it been possible for Kempton to find this information. Kempton calculated the ratio himself and found it to be 0,08. In order to be conservative Kempton uses 0,10. For the further analysis' 0,10 will be used. Effort should be put into revealing the actual numbers in further analysis'. The contracted capacity (P_{contr}) is +/- 32 MW and +/- 140 MW for primary reserves and regulation respectively, the t_{contr} is defined as a yr (8.760 hrs) (in order not to be influenced by time a year. The $R_{d\text{-}c}$ is e.g. expected to be higher in windy month than in more calm months). Kempton (2004) found that primary reserves and regulation was called for approximately 400 times/day. One calendar day (24 hrs) is equivalent to 1440 minutes. Since Kempton uses a $R_{d\text{-}c}$ of 0,1, then this is equal to 144 minutes/day and an average dispatch time of 21,6 seconds.[16]

Power and energy capacity of vehicles
Three factors limit the power an electric vehicle can provide to the grid. 1) the current-carrying capacity of the wires, 2) the stored energy in the vehicle and 3) the rated maximum power of the vehicle’s power electronics. The lowest of these three limits is the maximum power capability of the vehicle to grid (V2G) configuration. Since new batteries often have c-rates of 5, 10 or even more, the rated maximum power of the vehicle’s power electronics most often won’t be the limiting factor in plug-in hybrids or full BEVs. First equations to calculate the limit on V2G by line capacity is made. Then equations to calculate the limit on V2G power be the vehicle’s stored energy divided by the dispatch time is made. Then two vehicles defined earlier (BEV and hybrid HFCV) are analysed across the markets of primary reserves, regulation and spinning reserves.

Vehicle-internal circuits for electric vehicles are typically upwards of 30 KW as e.g. the Norwegian Th!nk. The Th!nk however has a limited top speed of 100 km/hr. If motorway speeds of 130 or more km/hr are needed more KW are needed. In comparison the smallest new cars in Denmark, which are selling really well, have a top speed of at least 155 km/h and have at least a 50 KW engine.[17] The building-wiring maximum is number of phases multiplied by voltage and ampere capacity of the line.

$$P_{\text{line}} = \text{PVA} \tag{2}$$

P_{line} is power limit imposed by the line in watts (here usually expressed in kW), P the number of phases (dimensionless), V the line voltage, and A is the maximum rated current in amperes. An average Danish house built in the 1960’s to 1970’s and a new house maximum power capacity is typically 19,2 and 30 KW respectively.[18] The average draw is close to 1 KW. On the vehicle side a 18,24 KW charger (3-phased, 380 V, 16 Amp) is assumed to become the standard.

Now the limit on V2G power imposed by the stored on-board energy divided by the time it is drawn is analysed. More specifically this limit is the onboard energy storage less energy used and needed for planned travel, times the efficiency of converting stored energy to grid power, all divided by the duration of time the energy is dispatched. This is calculated as:

$$P_{\text{vehicle}} = \frac{\left(E_{\text{s}} - \dfrac{d_{\text{d}} + d_{\text{rb}}}{\eta_{\text{veh}}} \right) \eta_{\text{inv}}}{t_{\text{disp}}} \tag{3}$$

Where $p_{vehicle}$ is maximum power from V2G in KW, Es the stored energy available as DC kWh to the converter, d_d the distance driven in km since the energy storage was full, d_{rb} the distance in km of range buffer required by the driver, η_{veh} the vehicle driving efficiency in km/KWh, η_{inv} the electrical conversion efficiency of the DC to AC inverter (dimensionless), and t_{disp} is time the vehicle‘s stored energy is dispatched in hours. d_d is defined as the average km driven on a daily basis in a Danish car, which is 45 km. 32 km is used as range buffer (d_{rb}) as described earlier.

The time dispatched (t_{disp}) will depend on the electricity market. For spinning reserves, although typical dispatches are 10 min, we calculate based on t_{disp} = 1 h here to insure that a 1-h contract

[16] 144 minutes per day where dispatches take place/ 400 dispatches pr. day * 60 seconds per minute = 21,6 sec. per dispatch in average.
[17] The triplets Toyota Aygo, Citroen C1 and Peugeot 107 are in combination by far the most popular car in Denmark. These cars have a top-speed of 157 km/h and a 50 KW engine in the basic gasoline editions.
[18] 3-phased, 400V, 16Amp and 3-phased, 400V, 25Amp.

requirement can be met. For regulation up and down, power in a battery vehicle can flow both ways; although regulation dispatch is typically only 1–4 min, t_{disp} of 20 min. is used to allow for the possibility of a long or repeated regulation up
sequence. The fuel cell vehicle can provide only regulation up (power flows from vehicle to grid), not regulation down (power from grid to vehicle), so it has no analogy to the battery EDV's recharge during regulation down. Thus, for example, a fuel cell vehicle parked 14 h and providing regulation up only, assuming R_{d-c} of 0.10, would have effective t_{disp} = 1.4 h. Power capacity of V2G is determined by the lower of the two limits, P_{line} or $P_{vehicle}$.

The BEV with 200 km range (BEV200) has a lithium battery with 22.0 kWh capacity, of which 100 % is considered available (E_s in Eq. (3)). It should be noted that very few lithium batteries are able to withstand depth of discharged (DoD) of 100 per cent. The rated vehicle efficiency (η_{veh}) is 9,10 km/KWh (~ 110 Wh/km) and we assume an efficient inverter of η_{inv} of 0.91.[19]

The hybrid HFCV will have a fuel cell system, a hydrogen tank and a 8,4 KWh lithium battery pack. This battery can be discharged 100% without excessive damage. From a specified all-electric range of 60 km, we calculate electric driving efficiency of 7,14 km/KWh. Here we assume V2G from the battery only; another operational V2G mode not calculated here would be running the fuel cell to generate power while the car is parked and plugged-in. We assume 4,2 kg of compressed hydrogen. The 4,2 kg represent 140 kWh at the lower heating value[20], but with the HFCVs 54 % efficient fuel cell system E_s is equal to 75,6 kWh electricity available from storage.[21] The vehicle efficiency (η_{veh}) is 7,14 km/kWh (140 Wh/km).[131,22]

The values for $P_{vehicle}$ for different electricity markets for the two EDVs are calculated using Eq. (3) and listed in the table below. For all vehicles, we assume d_d of 25,7 km and an efficient inverter of η_{inv} = 0.91.

Table 36 – Available power from two EDV's at three dispatch times

Vehicle type	Available power $P_{vehicle}$ (KW)		
	Spin. Res. (1h)	Reg. up (1,4 h)	Reg. up + Down (continuous per 0,33 h)
1) BEV200	14,5	10,4	43,6 + 8,0
2a) Hybrid HFCV, battery	4,1	3,0	12,4 + 10,6
2b) Hybrid HFCV, H2 storage	61,3	43,8	0 + 0
2) Hybrid HFCV battery & H2 storage	65,4	46,7	12,4 + 10,6

The fuel cell can provide more power for spinning reserves, whereas the battery in the BEV or in the hybrid HFCV can provide more regulation because they provide both regulation up and down. For example, the BEV200 provides 43,6 KW regulation up plus 8,0 KW down, that is 51,6 KW of revenue from regulation; the battery in the hybrid HFCV provides 12,4 KW regulation up and 10,6 KW regulation down. When comparing the BEV and hybrid HFCV, note that our assumed 25,7 km (16 miles) of electric-mode driving largely reduce the BEV battery capacity available (given lower η_{veh}). This leaves only 14,5 kW for 1 h spinning reserve. The capacity is thereby reduced by 7,5 KWh for the BEV and by to 4,1 KWh for the hybrid HFCV. In some situations, such as V2G being used for wind power backup, it is reasonable to assume advance notice on need for spinning reserves, so that hybrid driving could be done in constant-recharge mode, leaving full battery capacity available.

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[19] A 93 % efficient charger is assumed. When used as an inverter a 91 % efficiency is assumed.
[20] 4,2 kg hydrogen * 33,33 KWh/kg hydrogen (LHV).
[21] Assuming 54% fuel cell system efficiency, 97% electric motor efficiency and 15% regenerating.
[22] Concawe assume 0,7 kg hydrogen pr. 100 km. 0,7 kg H2 * 33,33 KWh/kg * 0,6 tank-to-wheel efficiency /100 km * 1000 W/KW = 140 Wh/km.

Available V2G power is the lesser of $P_{vehicle}$, from Table 36, and P_{line}, from Eq. (2). If we assume a residential line limit of 18,2 kW,[23] Table 36 shows that the BEV200 vehicle is limited by storage ($P_{vehicle}$) for spinning reserves and by P_{line} for regulation services. By contrast, the hybrid HFCV has high $P_{vehicle}$ values, as shown in Table 36, thus the assumed 18,2 kW P_{line} would limit it for both markets. These limits in turn might motivate upgrade to a larger kW line connection.

F.4.1 Revenue versus cost of V2G

The economic value of V2G is the revenue minus the cost. Equations for each are derived in the next two sections, followed by examples.

F.4.1.1. Revenue equations

The formulas for calculating revenue depend on the market that the V2G power is sold into. For markets that pay only for energy, such as peak power and base load power, revenue is simply the product of price and energy dispatched. This can also be expanded, since energy is *P t*,

$$r = p_{el} E_{disp} = p_{el} P_{disp}\, t_{disp} \qquad (4)$$

where r is the total revenue in DKK, p_{el} the market rate of electricity in DKK/kWh, P_{disp} the power dispatched in kW (for peak power P_{disp} is equal to P, the power available for V2G), and t_{disp} is the total time the power is dispatched in hours. (Throughout, we shall use capital P for power and lower-case p for price.) On an annual basis, peak power revenue is computed by summing up the revenue for only those hours that the market rate (p_{el}) is higher than the cost of energy from V2G (c_{en}, discussed later). For spinning reserves and regulation services the revenue derives from two sources: a "capacity payment" and an "energy payment." The capacity payment is for the maximum capacity contracted for the time duration (regardless of whether used or not). For V2G, capacity is paid only if vehicles are parked and available (e.g., plugged-in, enough fuel or charge, and contract for this hour has been confirmed). The energy payment is for the actual KWh produced; this term is equivalent to Eq. (4). Eq. (5) calculates revenue from either spinning reserves or regulation services, with the first term being the capacity payment and the second term the energy payment.

$$r = \left(p_{cap}\, P\, t_{plug}\right) + \left(p_{el}\, E_{disp}\right) \qquad (5)$$

where p_{cap} is the capacity price in DKK/KW-h, p_{el} is the electricity price in DKK/KWh, P is the contracted capacity available (the lower of $P_{vehicle}$ and P_{line}), t_{plug} is the time in hours the EDV is plugged in and available, and E_{disp} is the energy dispatched in KWh. (Note that the capacity price unit, DKK/KW-h, means DKK per KW capacity available during 1 h - whether used or not - whereas energy price units are the more familiar DKK/KWh.)

For spinning reserves, E_{disp} can be calculated as the sum of dispatches,

$$E_{disp} = \sum_{i=1}^{N_{disp}} P_{disp}\, t_{disp} \qquad (6)$$

where N_{disp} is the number of dispatches, P_{disp} the power of each (presumably equal to the vehicle capacity P), and t_{disp} is the duration of each dispatch in hours. A typical spinning reserves contract sets a maximum of 20 dispatches per year and a typical dispatch is 10 min long, so the total E_{disp} will be rather small. For regulation services, there can be 400 dispatches per day, varying in power (P_{disp}). In production, these would likely be metered as net energy over the metered time period, E_{disp} in Eq. (5). For this article, to estimate revenue we approximate the sum of P_{disp} by using the average dispatch to contract ratio ($R_{d\text{–}c}$) defined by Eq. (1), and rearrange Eq. (6) as Eq. (7)

[23] Assuming 3-phased 16A * 380V.

$$E_{disp} R_{d\text{-}c} P t_{plug} \tag{7}$$

Thus, for forecasting regulation services revenue (in a forecast, energy is estimated, not metered), Eq. (7) is substituted into Eq. (5), becoming Eq. (8),

$$r = p_{cap} P t_{plug} + p_{el} R_{d\text{-}c} P t_{plug} \tag{8}$$

F.4.2 Cost equations

The cost of V2G is computed from purchased energy, wear, and capital cost. The energy and wear for V2G are those incurred above energy and wear for the primary function of the vehicle, transportation. Similarly, the capital cost is that of additional equipment needed for V2G but not for driving. Assuming an annual basis, the general formula for cost is

$$c = c_{en} E_{disp} + c_{ac} \tag{9}$$

where c is the total cost per year, c_{en} the cost per energy unit produced (calculated below), E_{disp} the electric energy dispatched in the year, and c_{ac} is the annualized capital cost (calculated below). For spinning reserves, again E_{disp} would be computed by Eq. (6) and used in Eq. (9) to obtain annual cost. For regulation, substituting Eq. (7) for E_{disp} into Eq. (9), the total annual cost to provide regulation is

$$c = c_{en} R_{d\text{-}c} P t_{plug} + c_{ac} \tag{10}$$

where c_{en} is the per kWh cost to produce electricity (also used in Eq. (9)). The equation for c_{en} includes a purchased energy term and an equipment degradation term

$$c_{en} = \frac{c_{pe}}{\eta_{conv}} + c_d \tag{11}$$

where c_{pe} is the purchased energy cost, and c_d is the cost of equipment degradation (wear) due to the extra use for V2G, in DKK/KWh of delivered electricity. The purchased energy cost c_{pe} is the cost of electricity, hydrogen, natural gas, or gasoline, expressed in the native fuel cost units (e.g., DKK/kg H2), and η_{conv} is the efficiency of the vehicle's conversion of fuel to electricity (or conversion of electricity through storage back to electricity). The units of η_{conv} are units of electricity per unit of purchased fuel. Thus Eq. (11)'s computed c_{en}, the cost of delivering a unit of electricity, is expressed in DKK/KWh regardless of the vehicle's fuel. Degradation cost, c_d, is calculated as wear for V2G due to extra running time on a hybrid engine or fuel cell, or extra cycling of a battery. For a fuel cell vehicle or hybrid running in motor-generator mode, degradation cost is

$$c_d = \frac{c_{engine}}{L_h} \tag{12}$$

where c_{engine} is the capital cost per kW of the engine or fuel cell, including replacement labor in DKK/kWh, and L_h is the engine or fuel cell lifetime in hours. The degradation cost, c_d is thus expressed in DKK/kWh. For a battery vehicle, c_d is

$$c_d = \frac{c_{bat}}{L_{ET}} \tag{13}$$

where c_{bat} is battery capital cost in DKK (including replacement labor), and L_{ET} is battery lifetime throughput energy in KWh for the particular cycling regime (discussed below). The cost of degradation is zero if the vehicle life is less than the engine, fuel cell, or battery life due to driving plus V2G degradation, or if the battery's shelf life is reached before the degradation/wear life,

$$c_d = 0 \tag{14}$$

Battery lifetime is often expressed in cycles, measured at a specific depth-of-discharge. For Eq. (13), we express battery life in energy throughput, L_{ET}, defined as

$$L_{ET} = L_c\, E_s\, \mathrm{DoD} \tag{15}$$

where L_c is lifetime in cycles, E_s the total energy storage of the battery, and DoD is the depth-of-discharge for which L_c was determined. Shallow cycling normally has less impact on battery lifetime than the more commonly reported deep cycling. It does however heavily depend on the battery type and manufacturer. Here we base battery life parameters on 100% discharge test cycle for peak power or spinning reserves. To make financial decisions, calculations are typically made on a yearly basis and capital cost is annualized. One way to annualize a single capital cost is to multiply it by the capital recovery factor (CRF) as expanded in Eq. (16)

$$c_{ac} = c_c\, \mathrm{CRF} = c_c \frac{d}{1-(1+d)^{-n}} \tag{16}$$

Where c_{ac} is the annualized capital cost in DKK/year, c_c the total capital cost in DKK, d the discount rate, and n is the number of years the device will last.

F.4.3 BEV and hybrid HFCV providing regulation services

For calculation of revenue and cost, we use the same BEV and hybrid HFCV discussed earlier, providing regulation for the 2006 Nordpool market. Revenue is calculated with Eq. (8). This vehicle's parameters for Eq. (8) are listed in Table 37 and described under "comments." The last entry is the resulting computed revenue.

Table 37 – Revenue from battery and fuel cell vehicles providing regulation

Revenue parameters	BEV200	Batt. In hybrid HFCV	Comments
P (KW)	18,24	18,24	*P*line because *P*line < *P*vehicle. 3 phase, 380 V, 16 A
P_{cap} (DKK/KW-h)	1,47	1,47	In DK there is a combined capacity and electricity payment pr. month*
$P_{el\,reg.}$ (DKK/KWh)	0,00	0,00	See above note and page 22
t_{plug} (h/year)	6.570	6.570	Assume 18 hrs/day, 365 day/year
$R_{d\text{-}c}$	0,10	0,10	Eq. (1). Kempton use 0,1. This number is likely to be higher in DK
r(DKK)/vehicle/yr	176.191	176.191	Revenue, result by Eq. (8)

*((816.262 DKK/MW-h/month for primary reserves) + (277.607 DKK/MW-h/month for regulation))/(31 days pr. month * 24 hrs/day)/1000 MW/KW.

The total annual revenue calculated by Eq. (8) for the BEV and for the battery in the hybrid HFCV is DKK 176.191 with DKK 176.191 from capacity payments and DKK 0 from energy payments. The DKK 0 from energy payment is a result of the Energinet.dk rules where one is paid a monthly fee to put a certain amount of MW at Energinet.dk's disposal (see chapter B.2.). The payment is independent of the energy actually delivered and/or withdrawn to/from the grid. It has to be noted that there is a high possibility that the payment was extraordinary high in the month for which we know what the payment has been. Further data collection will reveal whether this is the case or not. In comparison Kempton gets revenue that is app. 5 times smaller (less than 5.000 USD).

Next we calculate costs for BEV and the hybrid HFCV to provide regulation services, using the cost parameters in and Eq. (10). As shown in Table 38, the annual cost for BEV and the hybrid HFCV-provided regulation (battery only in hybrid HFCV) is DKK 14.449 and 10.721 respectively. The net profit (revenue in Table 37 minus cost in Table 38) is DKK 161.742 for the BEV and DKK 165.470 for the hybrid HFCV a year.

Table 38 – Cost of batteries in BEV and hybrid HFCV providing regulation

Cost parameters	BEV200	Batt. inHybrid HFCV	Comments
c_{pe} (DKK/KWh)	0,65	0,65	Private consumers pay app. 3 times more for electricity.
η_{sys} (%)	79	79	Round-trip electrical efficiency ($\eta_{charger}$ $\eta_{el\text{-}el}$ η_{inv})
c_{bat} (DKK)	39.567	16.203	250 $/KWh * 6,6 DKK/$ * 21,98 KWh(BEV), 7,82 KWh (hybrid HFCV) + 10 h replacement labor * 50 ($/h)
c_d (DKK/KWh)	0,26	0,30	By eq. (13)
c_{en} (DKK/KWh)	1,08	1,12	By. Eq. (11)
L_{ET} (KWh)	158.476	56.382	BEV: 21,98 KWh battery @ 100 % DoD @ 7000 cycles. For shallow DoD we assume 1,03 times higher L_{ET} (see Table 23 - A123 batteries)
C_c (DKK)	12.540	12.540	On-board incremental cost 400 $ * 6,6 DKK/$ + wiring upgrade 1500 $
C_{ac} (DKK/year)	1.486	1.486	By eq. (16), assuming d = 0,1, n = 19,5 years, thus CRF = 0,12
c (DKK)	14.449	10.721	Cost, results by eq. (10), assuming P = 18,2 KW and t_{plug} = 6570 h

* If the plug capacity in a residence is to be greater than 3,68 KW (230 V 16 A), we assume wiring costs of 9.900 DKK (1.500 $ * 6,6 DKK/$) for 18,2 KW (3-phased 380 V 16 A).

The difference between the revenue and cost of providing regulation is much larger than what can be expected to be seen in reality. The error is most likely closely linked to the payment pr. mw-h, the $R_{d\text{-}c}$ ratio and the technology used to hybridize the Danish electricity grid.

It is very likely that the payment pr. MW-h was high in the two month for which we have date. Data for more months are needed in order to get a better estimate of the size of this number.

In West Denmark there is a high share of renewable energy. The fluctuating windpower largely increases the need for hybridization. In the table below is seen what happens to the cost of battery and fuel cell vehicles providing regulation if the $R_{d\text{-}c}$ ratio is 0,1, 0,5 and 1,0 respectively.

Table 39 – Cost of batteries in BEV and hybrid HFCV providing regulation at different Rd-c ratios

$R_{d\text{-}c}$	BEV c (DKK)	Batt. In hybrid HFCV c (DKK)
0,1	14.449	10.721
0,5	66.305	47.662
1,0	131.124	93.838

In the above table it is seen that the costs of providing regulation (in DKK/year) is largely influenced by the size of the $R_{d\text{-}c}$ ratio. Further information should be gathered regarding this subject.

It is believed that a large share of the regulation capacity in Denmark comes from coal fired power plants that diverts a small share of the steam to two small turbines that run constantly. One of these turbines is normally grid connected where as the other isn't. If up regulating power is needed the second turbine is connected to the grid, whereas is down regulation is needed the switch to the first turbine is turned off. There is a large energy loss associated with this kind of up and down regulating and it seems as if the capital costs are high as well. It Is likely that other technologies are used in the US (e.g. flying wheels), but that the assumed high Rd-c ratio in West-Denmark makes the coal fired type the best and/or cheapest choice. Further knowledge is needed regarding what kind of technologies is used where and why.

Furthermore the relatively size of the cost for BEV and hybrid HFCV is important. From Table 38 it is seen that the lowest costs are associate with the battery in the hybrid HFCV. This is due to the lack of range buffer in the hybrid HFCV compared to the BEV. When using uniform batteryprices pr. KWh (250 USD/KWh), then the capital costs naturally becomes lower for the battery in the hybrid HFCV compared to the battery in the BEV. In reality a small battery (measured In KWh) will most likely be more expensive pr. KWh than a larger battery. This is primarily so because of the higher charging and discharging abilities needed in a small battery compared to a larger battery. It is therefore in reality very hard based on the available datas to conclude which of the two possibilities that in reality will offer the lowest costs.

Which possibility that provide the lowest costs is very important, since it is the marginal cost that will decide how the regulation and spinning reserves market will function in the future. The technology with the lowest marginal cost is expected to capture all of the market, and only in the event that this technology can not cover all of the needs, the next best (cheapest) technology will come into play. If this is not enough to cover the needs, then the 3rd cheapest technology will come into play etc.

F.4.4 BEV and hybrid HFCV providing spinning reserves

For spinning reserves fuel cell vehicles is in general better matched to the demands. That is because of the higher energy needs compared to regulation services. Values of the parameters in Eq. (5) are listed in Table 40 for this particular example. As shown in Table 40, the revenue for BEV and hybrid HFCVs selling spinning reserves is DKK 12.131 and DKK 12.131 respectively. It should be noted that one can only use either the battery or the fuel cell at the same time. One can therefore not add the numbers for the battery and the fuel cell system in the hybrid HFCV. To calculate the annual costs for providing spinning reserves for the BEV200 and the hybrid HFCVs we use the values shown in Table 41, with Eqs. (9) and (11).

Table 40 – Revenue from battery & fuel cell vehicles providing spinning reserves

Revenue parameters	BEV	hybrid HFCV		Comments
	BEV200	Batt.	H2 & FC	
P (KW)	18,24	12,54	18,24	Assume P = Pline = Pdisp
p_{cap} (DKK/KW-h)	0,07	0,07	0,07	(38,37+35,34 DKK/MW-h)/1000 M/K (see chapter B.3)
p_{el} spin. (DKK/KWh)	0,81	0,81	0,81	(%27,38 + 281,97 DKK/MWh)/1000 M/K (see chapter B.3)
t_{plug} (h/year)	6.570	6.570	6.570	Plugged in daily, 18 (h/day) * 365 (day/year)
E_{disp} (KWh)	365	365	365	Assume 20 calls a year, each of max. capacity (per Eq. (6))
r (DKK)	9.128	6.370	9.128	Revenue, result by Eq. (5)

Table 41 – Cost of battery and fuel cell vehicles providing spinning reserves

Cost paramters	BEV	hybrid HFCV		
	BEV200	Batt.	H2	Comments
$c_{pe\ high}$ (DKK/KWh)	0,98	0,98	2,40	El: Industry price at high consumption * 3/2. H2: 80 DKK/kg / 33,33 KWh/kg H2
$c_{pe\ ave.}$ (DKK/KWh)	0,65	0,65	0,93	El: Industry price at high consumption. H2: 31 DKK/kg / 33,33 KWh/kg H2
$c_{pe\ low}$ (DKK/KWh)	0,38	0,38	0,72	El: Industry price at high consumption * 2/3. H2: 24 DKK/kg / 33,33 KWh/kg H2
η_{conv} (KWh/kg H2)	0,85	0,85	0,49	Batteries: (0,93 charger * 0,91 inv.). FC: (0,54 FC * 0,91 inv.)
c_d (DKK/KWh)	0,2572	0,2916	0,0660	Lh = 10.000 and c_{engine} = 100 €/KW (Eq. (12))
$c_{en\ high}$ (DKK/KWh) or (DKK/kg H2)	1,41	1,45	4,95	Eq. (11)
$c_{en\ ave.}$ (DKK/KWh) or (DKK/kg H2)	1,02	1,06	1,96	Eq. (11)
$c_{en\ low}$ (DKK/KWh) or (DKK/kg H2)	0,71	0,75	1,53	Eq. (11)
c_{ac} (DKK/year)	1.486	1.486	1.486	Assuming 19,5 yrs lifetime of car.
c (DKK(high))	1.999	2.013	3.292	Per Eq. (11), high H2 cost
c (DKK(average))	1.859	1.873	2.200	Per Eq. (11). average H2 cost
c (DKK(low))	1.745	1.759	2.044	Per Eq. (11), low H2 cost

Amortized as shown by Eq. (12) this gives an annual value of c_{ac} = DKK 1.486. The total annual cost based on Eq. (5) and the values in Table 41, using average electricity in BEV200 is DKK 1.859. Using the average estimate for hydrogen the total cost is DKK 2.200. Thus, given the above assumptions, the net annual revenue is DKK 7.269 for the BEV200, DKK 6.928 at average hydrogen costs. These figures illustrate that this result is not very sensitive to projected hydrogen prices, nor to energy payments (DKK/kWh), because spinning reserves involve very little energy transfer. However, the result is very sensitive to the capacity price for spinning reserves. More generally, fuel cell spinning reserves is economically viable only with a combination of good market prices and moderate capital costs; it is not sensitive to hydrogen costs.

F.4.6 Business analysis conclusions

We conducted technical analysis to understand the capacity of vehicles to provide power with minimal compromise of their primary function, transportation. We also investigated two major electricity markets, to find the best match of vehicle types to electric markets. To investigate this quantitatively, we used equations to describe the available power and duration, and the costs and market value of these forms of power. The result we offer is a quantitative understanding of how electric drive vehicles can become part of the electrical grid, and methods for estimating the expected revenue and costs.

In the table below the net revenue from regulation and spinning reserves is seen. The preliminary results suggest that the battery in the hybrid HFCV provides the highest net revenue from regulation, whereas the net revenue origin from spinning reserves seems to be higher for the BEV compared to both the battery and the H2 fuel cell in the hybrid HFCV. It has to be noted that revenue from spinning reserves can only come form either the battery or from the fuel cell at a specific time since there is a bottleneck in the grid. The two numbers can therefore not be added.

Table 42 – Net revenue from regulation and spinding reserves

		plug-in hybrid HFCV	
Summary - Net revenue	BEV200	Batt.	H2 & FC
Regulation - Net revenue	161.741	165.470	0
Spinning reserves - Net revenue	7.269	4.496	6.928

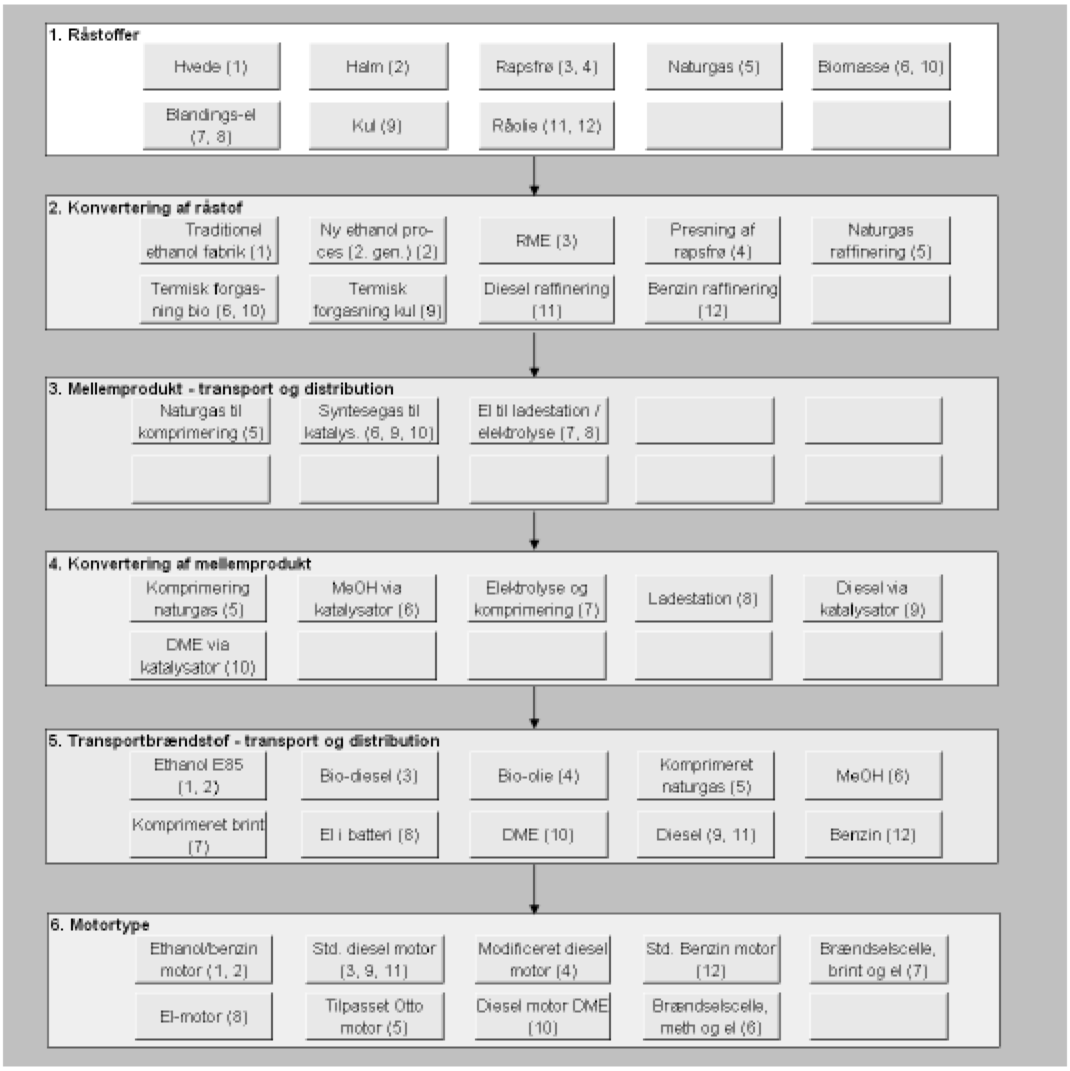
V2G most strongly competes for electricity when there is a capacity payment to be on line and available. This is the case for the ancillary service markets of spinning reserves and regulation. For these markets, even if V2G power loses money on each kWh sold, it can more than make up for that with the capacity payment. V2G may be able to compete when paid only for energy, but only when electricity prices are unusually high. Existing electricity markets have been the focus of this analysis, because their prices are known and they offer an annual revenue stream to help move V2G innovations forward. In the process, V2G would improve the reliability and reduce the costs of the electric system. As V2G begins to saturate these high value markets, it will be positioned to play a more fundamental role - storage for the emerging 21st century electric system based primarily on intermittent renewable energy sources.

APPENDIXES

Appendix 1 – Energy chain structure

From "Alternative drivmidler i transportsektoren - COWI beregningsmodel"[132] the term 4. conversion of middleproduct" (4. konvertering af mellemprodukt) is divided into "1. conversion" and "2. storage". The term "5. transport fuel and distribution" (5. transport brændstof og distribution) is in this report named "3. distribution". The term "6. Motor type" (6. motortype) is divided into "4. storage in car", "5. conversion in car" and "6. energy use".

All 6 above outlined steps are used for hydrogen, but only step 1, 5 and 6 are used when analysing batteries for the use in vehicles in this report. Electricity in battery (el i batteri) in reality belongs to both "5. transport fuel and distribution" and to "6. motortype", since the electricity flows into the battery, is stored in the battery and is withdrawn from the battery – all of which incurs (small) losses.



Appendix 2 – Vehicles data

All vehicles are assumed to have an actual lifetime of 13 years. 3 per cent interest rate is used and an exchange rate of 6.6 $/DKK.
The data presented is based on the Danish Energy Authority, 2008.[133] The following adjustments have been made to the HFCV and the BEV by H2Logic:

The batteries are assumed to be 500$/kWh now and 250 $/kWh in 2025 similar to the Danish Energy Authority, 2008 however the lifetime is expected to increase from 6 to 13 years here instead of to 16 years used in the Danish Energy Authority, 2008. The range of the BEV is approx. 135 km in the 2006 vehicle and 200 km in the 2025 vehicle.

The present HFCV and hybrid HFCV is based on Honda FCX Clarity, which has a range of 386 km (240 miles) when using 4,1 kg h2.[134] The future HFCV and hybrid HFCV are expected to use 0,7 kg hydrogen pr. 100 km.[135] The future costs of HFCV are based on the Danish Energy Authority, 2008[136] however the battery costs are based in the inputs above. The hybrid HFCV for 2008 and 2025 is based on the Honda with batteries equal to 60 km range and the specifications are connected to some uncertainties. The dataset for future hybrid HFCV is based on estimates made by H2Logic. The total range of the future hybrid HFCV is approx. 600 km on electricity from hydrogen and approx. 60 km on electricity from batteries.

In the tables below the data for vehicle is presented.

	ICE Diesel std.		ICE Diesel mod.		ICE petrol std./E85/Flex	
Time horizon	2006	2025	2006	2025	2006	2025
GJ mech/GJ (input)	0.21	0.25	0.21	0.25	0.16	0.235
Vehicle inv. (DKK)	86,000	86,000	98,000	98,000	77,000	77,000
Annual inv. Costs (DKK/year)	8,087	8,087	9,215	9,215	7,240	7,240
GJ mech/year	6.55	6.55	6.55	6.55	6.44	6.44
O&M (DKK/GJ mech)	962	946	962	962	979	979
Battery (DKK/year)	0	0	0	0	0	0
Total O&M (DKK/year)	6,301	6,196	6,301	6,301	6,305	6,305
Annual costs (DKK/year)	14,388	14,283	15,516	15,516	13,545	13,545

	HFCV		Hybrid HFCV		BEV	
Time horizon	2008	2025	2008	2025	2006	2025
GJ mech/GJ (input)	0.6	0.6	0.74	0,82	0.79	0.90
Vehicle inv. (DKK)	644,952	126,000	644,952	126,000	87,000	87,000
Annual inv. Costs (DKK/year)	60,645	11,848	60,645	11,848	8,181	8,181
GJ mech/year	7.52	7.52	7.52	7.52	6.83	6.83
O&M (DKK/GJ mech)	837	837	837	837	923	923
Battery (DKK/year)	4,386	931	6,433	1,210	11,184	3,413
Total O&M (DKK/year)	10,680	7,225	12,727	7,504	17,484	9,713
Annual costs (DKK/year)	71,325	19,073	73,372	19,352	25,665	17,894

Appendix 3 – Hydrogen storage data

Different hydrogen storage technologies are available, however significant problems in identifying good storage technologies is still present. One challenge is to identify the right onboard storage technology. The other challenge is to identify a good pathway to distribute and store the hydrogen before it is made available for the hydrogen vehicle. The weight and volume, the efficiency and the costs are some of the major challenges for hydrogen storage.

The data about hydrogen storage technologies presented below are translated from Sørensen, 2001.[137] For further information about the technologies please refer to the original publication.

Hydrogen storage		Large pressure tank		Small pressure tank		Underground cavern	
		2001	2030-2050	2001	2030-2050	2001	2030-2050
Material		Steel		Steel		Underground	
Storage media		Air		Air		Air	
Operation temp.	°C	Atm.		Atm.		30-100	
Pressure	bar	10-15		100-200		50-200	
Total efficiency	% of H2 in	100		100		67	83
Axuillary power	kWh el./Nm3	0.1	0.08	0.24	0.19	0.17	0.14
Total eff. Incl. Aux.	% of H2 in	96	97	91	93	84	89
Capacity	GJ	50-100		<0.1		100-100,000	
Lifetime	Years	*25*	30	*30*		*20*	25
Inv. Costs	DKK/MJ	45	40	50	45	0.2	0.12

The Concawe future hydrogen storage costs for small pressure tanks are in comparison 575 Euros/kg.[138] 575 euros/kg is at 120 MJ/kg hydrogen equal to a cost of 36 DKK/MJ. One 50 l hydrogen steelcanister weighs 63,9 kgs and the price of steel is 6,75 DKK/kg. Therefore the steelprice of a bottle is 431 DKK. 50 liters at 200 bar is equal to 89,6 MJ. The steelprice of the canister is therefore 431 DKK/canister / 89,6 MJ = 4,8 DKK/MJ.

Hydrogen storage		Tank w. liquid gas (5 kg H2)		Tank w. liquid gas (1,000 kg H2)		Metal hydrates	
		2001	2030-2050	2001	2030-2050	2001	2030-2050
Material		Isolated steel		Isolated steel		Steel	Composite
Storage media		Cooled air		Cooled air		Metal hydrate	
Operation temp.	°C	-253		-253		50-100	
Pressure	bar	1-2		1-2		30-60	
Total efficiency	% of H2 in	89	95	89	95	100	
Axuillary power	kWh el./Nm3	0.9	0.85	0.9	0.85	0.17	0.14
Total eff. Incl. Aux.	% of H2 in	58	66	58	66	94	95
Capacity	GJ	<100	0.05-100	<100	0.05-100	0.5-10	0.5-60
Lifetime	Years	18	20	18	20	*20*	20
Inv. Costs	DKK/MJ	30	24	1.5	1.4	50	40

Appendix 4 – Bio-ethanol

For the analyses here the IBUS bio-ethanol concept is used. The data is based on inputs from Dong Energy, Risø National Laborotory and the Faculty of Life Sciences at Copenhagen University to the Danish Society of Engineers' (IDA) Energy Plan 2030 for a plant in 2006.[139]

With an energy input of 2,320 TJ straw, 36 GWh electricity and 497 TJ of steam/heat 948 TJ of bio-ethanol and 1,064 TJ biofuel is produced as well as 38 ton of feed (molasses 70 per cent dry matter) or 295 TJ feed.

Such a plant is assumed placed in the vicinity of a large existing extraction plant that uses biomass as supplementary fuel and can produce the necessary steam and heat with a marginal efficiency of 167 per cent. The marginal additional biomass required is 2,320 TJ minus the 1,064 and 295 TJ to produce 961 TJ bio-ethanol. The additional biomass needed for heat steam is 497 TJ/1,67 equal to 298 TJ bio-fuel. That means that 1,259 TJ extra biomass is required to produce 948 TJ of ethanol (1 to 1.3). In addition 36 GWh electricity is required.

The costs of such a plant is 590 mio. DKK and 30 mio. DKK/year in O&M costs. The life time is 20 years. The enzymes are expected to drop in price from the current 0.95 DKK/liter biofuel (Novozymes, 2006) to 0.16 DKK/L biofuel in 2030. This corresponds to 7 mio. DKK/year in 2030.
In future plants more ethanol is not expected to be produced, however the heat/steam usage is expected to be reduced by 20 per cent and the electricity consumption by 30 per cent. The costs pr. L biofuel are expected to be reduced by 15 per cent. In the future the extraction plant is expected to run half of the hours in condensing mode, reducing the marginal efficiency to 130 per cent.

The E85 data used in the scenarios is listed in the table below.

		2006	2030	CanDan 2030 E85 (85 %)	Petrol (15 %)
Straw	TJ	2320	2320	28,813	
Biofuels incl. feed	TJ	-1359	-1359	-16,878	
Fuels for heat/steam	TJ	298	305	3,788	
Net biomass consumption	TJ	1259	1266	15,723	
Ethanol produced/petrol	TJ	948	948	11,647	2,055
Factor	-	1.3	1.35	1.35	
Inv. Costs	Mio. DKK	590	500	6,143	
O&M costs	Mio. DKK/year	30	25	307	
Enzym costs	Mio. DKK/year	42	7	86	
Electricity consumption	GWh	36	25	307	

Appendix 5 – Hydrogen cars

Hydrogen cars cumulative numbers (thousands)

DK #		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
USA	Scenario 1 Cum.			-	-	-	0,0	0,1	0,1	0,5	1,4	2,6	4,2	6,3	8,8	12,1	16,2							
	Scenario 2 Cum.			0,0	0,0	0,0	0,3	0,8	1,3	2,9	5,4	8,7	12,8	17,7	23,5	30,9	39,1							
	Scenario 3 Cum.			0,0	0,0	0,0	0,3	0,8	1,3	3,7	7,8	14,0	22,3	32,1	44,5	61,0	81,6							
Linde	Low uptake			-	-	-	-	0,2	1,9	5,0	8,1	11,2	14,7	21,3	30,6	39,9	49,4	60,6	73,0	85,6	100	117		
	High uptake			-	0,3	2,4	6,3	10,4	16,4	24,7	36,7	52,5	70,5	92,3	118	145	175	208	243	280	317	355		
HyWays	Low penetration	*										2,5										74,9	381	1.170
	Medium penetration	*										30,0										319	1.061	2.256
	High penetration	*										82,5										634	1.608	2.422
	Expected # of cars	2.264	2.298	2.331	2.358	2.380	2.402	2.420	2.440	2.459	2.479	2.500	2.519	2.540	2.558	2.577	2.593	2.612	2.627	2.644	2.660	2.676	2.956	3.250

Hydrogen cars cumulative (percentage)

DK %		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
USA	Scenario 1 Cum.	-	-	-	-	-	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,2	0,3	0,5	0,6							
	Scenario 2 Cum.	-	-	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,3	0,5	0,7	0,9	1,2	1,5							
	Scenario 3 Cum.	-	-	0,0	0,0	0,0	0,0	0,0	0,1	0,2	0,3	0,6	0,9	1,3	1,7	2,4	3,1							
Linde	Low uptake	-	-	-	-	-	-	0,0	0,1	0,2	0,3	0,4	0,6	0,8	1,2	1,5	1,9	2,3	2,8	3,2	3,8	4,4		
	High uptake	-	-	-	0,0	0,1	0,3	0,4	0,7	1,0	1,5	2,1	2,8	3,6	4,6	5,6	6,7	8,0	9,3	10,6	11,9	13,3		
HyWays	Low penetration											0,1											12,9	36,0
	Medium penetration											1,2											35,9	69,4
	High penetration											3,3											54,4	74,5

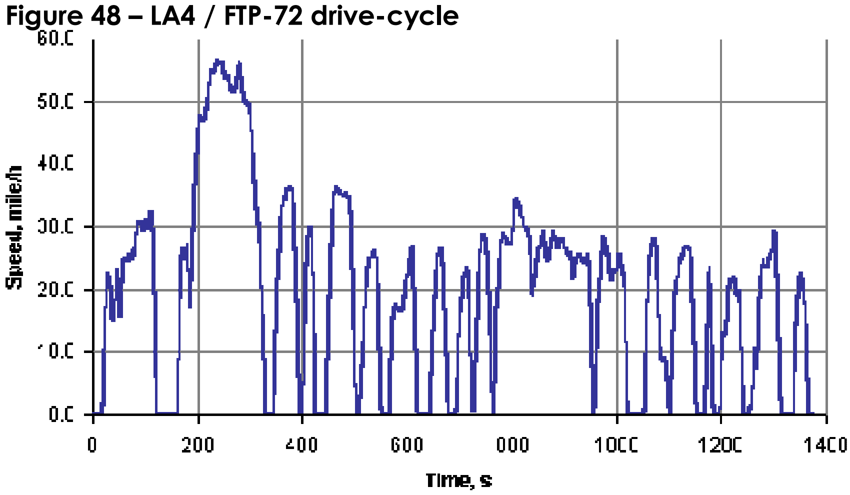
Power (MW) available if 74 KW pr. car in average

DK %		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
USA	Scenario 1 Cum.			-	-	-	2	5	9	40	101	192	314	466	649	893	1.198							
	Scenario 2 Cum.			0	1	2	20	56	93	215	398	642	946	1.312	1.739	2.287	2.897							
	Scenario 3 Cum.			0	1	2	20	56	93	276	581	1.038	1.647	2.379	3.293	4.512	6.036							
Linde	Low uptake			-	-	-	-	13	140	370	600	830	1.085	1.577	2.266	2.955	3.657	4.481	5.400	6.332	7.385	8.642		
	High uptake			-	19	179	466	766	1.213	1.825	2.719	3.887	5.215	6.830	8.713	10.749	12.919	15.383	17.993	20.725	23.463	26.297		
HyWays	Low penetration											185										5.546	28.220	86.592
	Medium penetration											2.220										23.569	78.535	166.931
	High penetration											6.105										46.940	119.005	179.198

Appendix 6 – Drive cycles

"The U.S. FTP-72 (Federal Test Procedure) cycle is also called Urban Dynamometer Driving Schedule (UDDS) or LA-4 cycle. The same engine driving cycle is known in Sweden as A10 or CVS (Constant Volume Sampler) cycle and in Australia as the ADR 27 (Australian Design Rules) cycle. The cycle simulates a urban route of 12.07 km (7.5 mi) with frequent stops. The maximum speed is 91.2 km/h (56.7 mi/h) and the average speed is 31.5 km/h (19.6 mi/h).

Figure 48 – LA4 / FTP-72 drive-cycle



The cycle consists of two phases: (1) 505s (5.78 km at 41.2 km average speed) and (2) 864s. The first phase begins with cold start. The two phases are separated by stopping the engine for 10 minutes. In the U.S. a weighting factors of 0.43 and 0.57 are applied to the first and second phase, respectively. In Sweden both phases have the same weighting factors. Emissions are expressed in g/mile or g/km".[140]

Appendix 6 - Nomenclature and worksheet for business analysis

This appendix lists the symbols, names, and units from the equations used in chapter F.4 Business analysis of balancing potential. In the tables below the data needed for equations in the business analysis are listed.

Table 43 – Data needed for equations in the business analysis

Parameter description	Symbols	Units
Line connection parameters		
Rated maximum circuit. **A**mpere	A	Amperes
Line **V**oltage	V	Volts
Vehicle parameters		
Energy **s**tored (available in inverter)	E_s	KWh
Efficiency **Veh**icle	η_{veh}	km/KWh
Efficiency of line AC to battery **charger**	$\eta_{charger}$	Dimensionless
Efficiency of **inv**erter from DC to line AC	η_{inv}	Dimensionless
Energy **recharhe**d to battery	$E_{recharge}$	KWh
Dep th-**of**-**d**ischarge	DoD	Dimensionless (0,00 - 1,00)
Number of years the device will last	n	Years
Efficiency of converting **el**ectricity to **el**ectricity	$\eta_{conv\ el\text{-}el}$	KWh_{out}/KWh_{in} (dimensionless)
--- I --- **gas**oline to **el**ectricity	$\eta_{conv\ gas\text{-}el}$	KWh/L
--- I --- **h**ydrogen to **el**ectricity	$\eta_{conv\ h2\text{-}el}$	KWh/kg H2
Lifetime in **h**ours **b**attery **e**lectric **v**ehicle, **batt**ery	$L_{hBEVbatt}$	Hrs
Lifetime in **h**ours **p**lug-in **h**ybrid **e**lectric **v**ehicles, **en**gine	$L_{hPHEVen}$	Hrs
Lifetime in **h**ours **p**lug-in **h**ybrid **h**ydrogen **f**uel **c**ell **v**ehicles, **f**uel **c**ell	$L_{hPHHFCVfc}$	Hrs
Lifetime in **c**ycles	L_c	Cycles (at given DOD)
Capital cost of prime mover	C_{engine} or C_{FC}	DKK/KW
Capital cost of **batt**ery	C_{batt}	DKK
Capital **c**ost (total c_c for on-board of vehicle and wiring upgrade)	c_c	DKK
Vehicle operational parameters		
Time **plug**ged in	t_{plug}	Hrs
Energy **recharge**d since plugged in	$E_{recharge}$	KWh
Distance **d**riven	d_d	Km
Distance **r**ange **b**uffer	d_{rb}	Km
Market parameters		
Ratio, **d**ispatch to **c**ontract	$R_{d\text{-}c}$	Dimensionless (0,00 - 1,00)
Time for one **disp**atch in hours	t_{disp}	Hrs
Time duration, **contr**acted capacity	t_{contr}	Hrs
Price to sell V2G **el**ectricity on **reg**ulation market	$p_{el\ reg.}$	DKK/KWh
Price to sell V2G **el**ectricity on **spin**ning market	$p_{el\ spin.}$	DKK/KWh
Price, **cap**acity **reg**ulation	$p_{cap\ reg.}$	DKK/KW-h

Price, **cap**acity **spin**ning reserves	$p_{cap\ spin.}$	DKK/KW-h
Cost for EDV to buy energy, **c**ost **p**rojected **e**nergy cost, **high**	$c_{pe\ high}$	DKK/Kwh, DKK/kg H2, DKK/L
Cost for EDV to buy energy, **c**ost **p**rojected **e**nergy cost, **ave**rage	$c_{pe\ ave.}$	DKK/Kwh, DKK/kg H2, DKK/L
Cost for EDV to buy energy, **c**ost **p**rojected **e**nergy cost, **low**	$c_{pe\ low}$	DKK/Kwh, DKK/kg H2, DKK/L
Power, **contr**acted capacity	P_{contr}	MW
Power of each **disp**atch	P_{disp}	KW
Power, contracted capacity available (the lower of $P_{vehicle}$ and P_{line})	P	KW
Number of **disp**atches	N_{disp}	Dimensionless
Discount rate	d	per cent

Table 44 – Variables calculated in the business analysis

Description	*Symbol*	Units	Equation
Dispatch to **c**ontract **r**atio	$R_{d\text{-}c} = E_{disp} / P_{contr} t_{contr}$	(dimensionless)	1
Power limit of **line** connection	$P_{line} = VA$	KW	2
Power limit of **vehicle**'s stored energy	$P_{vehicle} = (E_s - d_d + d_{rb} / \eta_{veh}) \eta_{inv} / t_{disp}$	KW	3
Total **r**evenue	$r = p_{el} E_{disp} = p_{el} P_{disp} t_{disp}$	DKK	4
Total **r**evenue	$r = (p_{cap} P t_{plug}) + (p_{el} E_{disp})$	DKK	5
Energy **disp**atches	$E_{disp} = N_{disp} \Sigma_{i=1} P_{disp} t_{disp}$	KWh	6
Energy dispatches	$E_{disp} = R_{d\text{-}c} P t_{plug}$	KWh	7
Total revenue	$r = p_{cap} P t_{plug} + p_{el} R_{d\text{-}c} P t_{plug}$	DKK	8
Total cost per year	$c = c_{en} E_{disp} + c_{ac}$	DKK/yr	9
Total cost per year	$c = c_{en} R_{d\text{-}c} P t_{plug} + c_{ac}$	DKK/yr	10
Cost per energy unit produced	$c_{en} = c_{pe} / \eta_{conv} + c_d$	DKK/KWh	11
Degration cost, engine or fuel cell	$c_d = c_{engine} / L_h$	DKK/KWh	12
Degration cost, battery	$c_d = c_{batt} / L_{ET}$	DKK/KWh	13
Degration cost	$c_d = 0$	DKK/KWh	14
Battery lifetime, in throughput	$L_{ET} = L_c E_s$ DoD	KWh	15
Annualized lifetime, in throughput	$c_{ac} = c_c$ CRF $= c_c\, d/(1 - (1 + d)^{-n})$	DKK/yr	16
CRF = Capital Recovery Factor		CRF	

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